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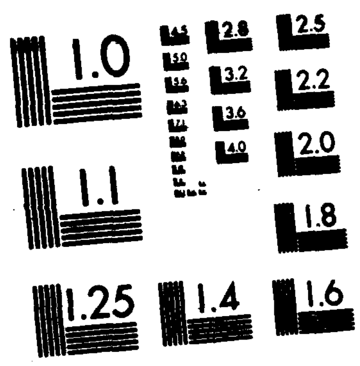

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An Investigation of Soviet Capabilities in Extended Range Arctic Ice Forecasting

Final Report
Contract N00014-85-C-0763
December 1987

Science Applications International Corporation

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Final Report
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December 1987

Prepared for
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

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EXECUTIVE SUMMARY

This review provides a substantial level of background information and insight into evolving Soviet approaches through the mid-1980's concerning monthly and seasonal forecasting of ice conditions and related environmental matters. Some recent significant changes in Soviet approaches and techniques to Arctic ice forecasting were identified. These are generally post-1980 trends and in some cases have not yet been addressed in their scientific literature. The majority of the most recent Soviet references are from news articles rather than professional publications. Recent pertinent trends include:

Recent trends in Soviet ice forecasting include:

1) rapid development in the use of satellite infrared, microwave, and side looking radar data relative to ice conditions in the last few years;

2) the continued emphasis on empirical or empirical/dynamic mixed models emphasizing application to regional problems; and

3) an arctic atmospheric circulation pattern change and a concomitant spatial shift of ice conditions within the Alaskan to Siberian sector that were most highly correlated with the ice flux through the Fram Strait.

The arctic atmospheric circulation pattern change was identified as a result of the evaluation work done by the author on a Soviet statistical model.

Both the finding of the high correlation between the Fram Strait ice flux and arctic sector ice conditions and the Arctic atmospheric circulation pattern shift is noteworthy in that it is thought to be new information to Western scientists. An article on this relationship has been submitted to the Geojournal for a special edition on the Arctic. Dr. John E. Walsh, who collaborated with the author on this study while filling the ONR Arctic Marine Science Chair, Naval Postgraduate School (NPS), is the co-author of the Geojournal article. Dr. Walsh, together with an NPS theses student, conducted one of the Soviet model evaluations addressed in Appendix B and conducted further investigation of the relationship between sea-surface-temperature (SST) anomalies and North Atlantic ice conditions. The student is continuing this line of investigation in his PhD thesis and at least one other NPS student is pursuing the SST/Ice relationship as a thesis subject at the master's level.

Abstract

The areal outflow of ice through Fram Strait during the period 1953-1984 is estimated on a monthly basis from the geostrophic wind and the ice concentration. Summer ice coverage in various sectors of the Arctic is then compared with the computed outflow through Fram Strait in various antecedent periods. Lag correlations indicate that interannual variations of summer ice severity in the Pacific side of the Arctic Basin are consistent with fluctuations of Fram Strait outflow during the previous 3-9 months. The findings suggest that above-normal outflow of multiyear ice during the winter/spring months may precondition the large-scale pack ice to respond more directly to offshore flow events during the ensuing months.

The areas of highest correlation with Fram Strait outflow undergo a pronounced shift in the early 1970's. Coincident changes in the large-scale circulation pattern imply that the source region of the Transpolar Drift Stream shifted westward from the Alaskan to the Siberian waters during this period.

INTRODUCTION

The objectives of this project, under ONR contract N00014-87-C-0039, included a review of unclassified Soviet literature on extended range arctic ice forecasting, evaluation of related Soviet capabilities and selection of suitable Soviet empirical models for test and evaluation. The findings and results were to be contained in a final report and, if appropriate, printed in open literature. These objectives will have been met with the submission and acceptance of this final report and the publishing of a paper entitled "Fram Strait Ice Flux Calculations and Associated Arctic Ice Conditions" which has been submitted to Geojournal for inclusion in a special Arctic Ice Issue. Additionally, a report on these findings was made at the 1987 Navy Symposium on Arctic/Cold Weather Operations of Surface Ships and will be published in the Proceedings.

Two of the originally planned tasks have not been addressed under this effort. The evaluation of U.S. data bases for evidence of cyclic characteristics associated with solar cycles, a key predictor used by Soviet researchers prior to the 1970's, was considered inappropriate in light of the early determination (in our literature review) of a general shift away from this approach by Soviet researchers. The second task not pursued at this time is the investigation of large scale atmospheric conditions during MIZEX periods. This task did not lend itself to, nor appear to provide a synergistic effort on the rest of the work. However, a phenomena related to both a Soviet forecasting approach and ice conditions in the Fram Strait/Greenland Sea region was investigated and is the main

theme of the article submitted for the special Arctic issue of the Geojournal.

The comments in the following survey report are based on the review of Soviet literature available to the authors through May 1987. This initial data set was from translated work through the mid 80's, but consisted primarily of Soviet works originally published prior to 1980. Several of the authors' findings, as stated in the following report, were modified as a result of cursory reviews of post 1980 Soviet material as well as from work by the authors which evolved out of the early findings of this project. Changes to specific findings based on pre-1980 literature are summarized in the Conclusions and Recommendations and annotated in the text where appropriate.

This report contains the following additional sections:

1) Approach,
2) Survey of Soviet Capabilities in Long-Range Forecasting for the Arctic, and
3) Conclusions and Recommendations

In addition there are three appendices providing details on:

A) Recent (1985 and 1986) Soviet Articles on Hydrometeorology,
B) Results of the Evaluation of Two Soviet Empirical Models, and
C) A Draft of an article submitted to Geojournal for inclusion in their special issue on Arctic topics, plus a copy of a presentation for the 1987 U.S. Navy Symposium on Arctic/Cold Weather Operations of Surface Ships.

The Geojournal article was co-authored by R. E. Englebretson and Dr. John E. Walsh who collaborated on this project while Dr. Walsh held the ONR funded Arctic Marine Science Chair, Naval Postgraduate School, Monterey, CA.

APPROACH

A review of unclassified translated Soviet literature from the late 1950's to early 1980's was conducted to obtain background information on the Soviet capabilities and procedures in Arctic long-range forecasting. It was found that the focus of Soviet approaches to the long-range forecasting problem shifted during the 1970's from one of external forcing (solar activity and earth orbital variations) and basic atmospheric responses (circulation typing), to one of internal direct physical forcing and response. The interactions of sea surface temperatures, regional pressure differences, ice conditions, and fluxes between polar and mid-latitude regions became the most frequently used parameters. Empirical/statistical models continued as the primary modeling approach throughout the period of review. The general lack of computer power or recent acquisition of computers, was on occasion noted as a reason for less comprehensive testing of models. Only near the beginning of the 1980's did the results of numerical dynamic modeling efforts begin to be addressed in the Soviet meteorological scientific literature, and then only by relatively junior researchers using models of limited sophistication. The preferences for empirical modeling over numerical dynamic modeling remains in strong evidence in the literature through the 1985-1986 time frame. Evidence that dynamic modeling has not yet overtaken the mainstream of Soviet environmental prediction was demonstrated by Dr. M. I. Budyko of the State Hydrological Institute, Leningrad who was the leader of the Soviet delegation to a 1986 U.S./U.S.S.R. meeting of experts on

the causes of recent climatic change. Dr. Michael C. MacCracken, leader of the U.S. delegation, reported that Dr. Budyko argued for empirical rather than theoretical approaches to solving problems of ecology, composition of the atmosphere, etc. Some appreciation of the Soviet scientists unawareness of numerical model limitations -- probably based on a general lack of exposure to them -- was noted during this meeting when the Soviet delegate expressed surprise at the fact that the results of various U.S. general circulation models (GCMs) provided differing results of the climatic effects by increasing CO_2 levels.

There is, however, evidence in the literature that a number of the young, rising Soviet scientists are dedicated to numerical model development. Their progress in environmental dynamic modeling is likely to be quite rapid in light of the knowledge that can be gleaned from years of work by U.S. and other scientists in addition to the extensive theoretical and data base resources developed by the Soviets. An additional factor that may provide rapid progress by the Soviets in the numerical weather prediction (NWP) area, would result from recognizing the extreme emphasis on dynamic models and computer power that prevailed in the U.S. scientific and operational fields from the early 1960's through recent time; that is, if just given a "large enough computer", the dynamic models could solve all the forecasting problems. The recognition of the limitations of NWP is nearly as important as the recognition of its usefulness. Therefore, for maximum utilization, an appropriate level of resources should be provided for upgrading the field/operational capabilities along with the resources

committed for central site computer/model enhancement. To date the Soviets appear to be more aligned with maintaining a strong input by man as well as a tendency to place the technology in the hands of the field forecasters vice sequestering it in convenient central sites. The Soviet history of approaching various arctic problems from a more analytical viewpoint than U.S. scientists provides them with a large array of regional and local models and algorithms. This approach lends itself more to solutions on local computers using in situ data than the U.S. approach of using large scale models at central computer sites with global data bases.

Two Soviet empirical long-range forecasting models were selected for review. Lebedev and Uralov (1977) presented regression equations for the Greenland Sea ice cover in terms of year-to-year persistence, October-February air temperatures from selected stations, and October-February sea-surface-temperatures (SST's) at two North Atlantic weather ships. Further details are provided in Appendix A. Explained fractions of variance are generally 30-60% at lead times of 3-6 months. Dr. Walsh and Gordon Fleming (NPS masters degree student) investigated the SST anomaly correlation with the North Atlantic ice edge and found significant correlations at lags of several months. The results of their findings are contained in Fleming's 1987 thesis entitled "Predictability of Ice Concentration in the High Latitude North Atlantic from Statistical Analysis of SST and Ice Concentration Data".

The work of Smirnov (1979) was selected for evaluation of forecasts for the Alaskan region. Smirnov produced 18 regression equations for the May-September Alaskan area ice

cover in terms of the preceding winter, spring, and summer environmental parameters of air temperatures at Point Barrow, pressure differences between Point Barrow and Alert, and the ice transport through the Fram Strait. Further details are provided in Appendix A.

The use of the Fram Strait ice flux was investigated in some detail by the authors as is has not been used in a similar manner by western researchers. It was found that nearly a complete loss of forecast skill occurred for both the Soviet and the independently derived U.S. regression equations for the period following about 1972. (See appendix B for details.) This led to further investigation which found evidence of a major shift in the Arctic sea level pressure circulation pattern before and after about 1972. The implication of such a circulation pattern shift on the source region for ice feeding into the Transpolar Drift as well as a general climate change are addressed in a paper being submitted to Geojournal. A draft of this paper is provided in Appendix C part 2. Also included in Appendix C part 1 is a copy of a paper submitted to the 1987 Navy Symposium on Arctic/Cold Weather Operations of Surface Ships. This paper provides an overview of the findings from this literature review and summary of Soviet capabilities and approaches.

A summary of the findings from the literature review and resulting survey of Soviet capabilities in long-range forecasting for the Arctic follows in the next section. A preface is attached that points out several recent findings in the literature obtained after the initial review.

SURVEY OF SOVIET CAPABILITIES IN LONG-RANGE FORECASTING FOR THE ARCTIC

This section summarizes the results of a survey of Soviet capabilities in long-range forecasting for the Arctic by John E. Walsh and Ronald E. Englebretson. Funding for the work was provided for Dr. Walsh through the ONR Arctic Marine Science Chair, Naval Postgraduate School, Monterey, California and under ONR Contract N00014-87-C-0039 via Navy Center for International Science and Technology (NCIST), Monterey, California for Mr. Englebretson. The review includes assessments of long-range forecasts of Arctic sea ice, weather and ocean variability derived from a preliminary survey of translated unclassified literature. The initial Soviet publishing dates extend through the 1970's with a few early 1980 references. The survey covered most issues of the major translated journals, together with assorted books and various other translated documents. Attempts were made to identify the key scientific personnel, recent trends or likely changes in methodologies, and the extent of operational utilization of the forecast products. The preceding statements in the Approach section reflects the rapidly changing Soviet technology and approaches to these problems.

1. Administrative Aspects

Nearly all published Soviet R&D work pertaining to Arctic long-range forecasting has been performed at the Arctic and Antarctic Research Institute (AANII) which has its main branch in Leningrad. When the administrative organization changed in the 1960's with the liquidation of the "Principal Board for the

Northern Sea Route", the scientific section of the AANII was transferred to the USSR Hydrometeorological Service. At that time the direction of Arctic marine operations was transferred to the Murmansk and Vladivostok ports (Tolstitov, 1982). Shortly thereafter, the literature indicates a shift of some Arctic research, especially for the North Atlantic sector, to a Murmansk branch of the AANII (e.g., Terziev, 1977).

The major scientific publication of the AANII is the quasi-annual volume, "Problems of the Arctic and the Antarctic" (PAA). For most of the period surveyed, this publication was edited by A.F. Treshnikov, the director of the AANII since 1960. On Treshnikov's 70th birthday in 1984, the editorship of PAA was assumed by B.A. Krutskih. A large number of the Soviet articles are from the journal Soviet Meteorology and Hydrology (Meteorologiya i Gidrologiya) (MG). The dates of the MG and PAA relate to the date of publication of the translated references, the original Soviet articles are typically from about 2 years earlier.

2. Long-Range Arctic Weather Forecasting

Through much of the 1950's and 1960's, the cornerstone of Soviet long-range weather forecasting was the "macrocirculation" typing system (E, C, W, M_1, M_2, Z). This typing system can be traced back to the previous generation of Soviet meteorologists (e.g., Vangengeim), and its leading proponent at the AANII during the 1960's and 1970's was A.A. Girs (1960, 1973, and 1981). While much of the developmental work on this system was done at the AANII, the system provided input to the Soviets' operational forecasts for the entire hemisphere until at least

the early 1970's (Livezey and Jamison, 1977). Multi-year changes in the frequency of these types were claimed to be attributable to cycles in solar (sunspot) activity and the solar-lunar tide (e.g., Karklin, 1975 and Dmitriev, 1975). Evidence of these cycles was also claimed to exist in sea ice variability (see Long-Range Sea Ice Forecasting section), presumably through variations in the dynamic and thermodynamic forcing of the ice by the atmosphere. Examples of the uses of these tools in constructing long-range forecasts of Arctic sea level pressure are given by Sancevich (1976). Volkov and Zakharov (1977) state a recurring theme from the Soviet papers of the 1970's and longer-term (multi-year) arctic forecasting: "The largest number of future-climate forecasts is now based on the hypothesis of solar control of climate variations". The solar approach was used by those authors to forecast a trend toward colder Arctic temperatures and more severe Soviet ice conditions through the 1990's. It should be noted that the solar-weather link was openly recognized as being quite subtle by some AANII scientists even in the early 1970's. Smirnov (1973), for example, notes the high-latitude SLP fields correlate highly with solar activity only when the SLP data are filtered by computing the differences running 7-year and 11-year means. Smirnov concludes that the "role of solar activity ... is <u>not</u> decisive even in the region of the most pronounced effect on the Northern Hemisphere troposphere". In a survey paper on Arctic variability, Antonov (1980) states that "<u>no</u> practically significant relationship of the fluctuations of terrestrial phenomena with solar activity has been established".

In recent years both internal and external assessments have placed Soviet capabilities in long-range weather forecasting into a more realistic perspective than implied by Soviet papers of the 1960's and 1970's. Livezey and Jamison (1977), for example, show that the skill of Soviet long range weather forecasts through the early 1970's was no better than control forecasts such as persistence -- although the Soviets' forecasts did display more skill for the Arctic than for other regions of the USSR. Volkov (1972) notes that the accuracy of long range forecasts even for the Arctic is not high: the frequency of correctly forecast signs of anomalies of Arctic temperature and pressure does not exceed 60-65%. Girs' work on the usefulness of the W/C/E typing to distinguish Arctic radiative regimes has been openly criticized by Volkov et al. (1968). Niko'skaya et al. (1977) of the AANII's Murmansk branch found little correlation between North Atlantic atmosphere/ice variability and Girs' types; Sancevich (1976) states that "Girs' method is useless for forecasts in the Arctic". Treshnikov's (1981) recent projection of future AANII activity in long-range weather forecasting is rather vague, referring to attempts at "further objectifying the method of analysis and forecasting of macro-synoptic processes". Treshnikov mentions neither solar activity nor tidal considerations in his discussion of future plans.

Recent Soviet reviews of the "state of the art" of weather forecasting in the USSR (Aristov and Ped, 1979 and Petrosyants, 1982) indicate that present methodologies are quite similar to those in the U.S. Short-range forecasts are based largely on LFM-type models and MOS procedures, although computer limitations are probably responsible for the use of only 4

layers in the model and for the frequent mention of model running time. (Petrosyants notes that Soviet participation in GARP was limited by the failure to acquire a CDC 7600 computer.) Long-range forecasting tools listed by Aristov and Ped include the statistics of persistence and extrapolation which are heavily used in the U.S. by NOAA/NMC's Long-Range Prediction Group. The weight given by the Soviets to North Atlantic SST, as well as to snow cover and soil moisture, appears to be greater than that at NMC. Marchuk's (1974a and b) method of diagnosing 30-day temperature anomalies in terms of adiabatic and non-adiabatic components seems to be the Soviets' most novel technique, and perhaps merits investigation by U.S. forecasters. Dynamical model forecasts to 30 days are apparently not utilized by the Soviets (probably because of computer limitations), thus the Soviets appear to lag the U.S. and Europeans in this regard. Petrosyants indicates that the Soviets attempt forecasts up to one year in advance, but no procedural details are given.

3. Oceanic Variability in the Arctic

Relative to U.S. efforts in Arctic science, the Soviets' major advantage appears to be their progress in the measurement, diagnosis, and perhaps the prediction of high-latitude oceanic variability. Two recently published texts (Regional Oceanography and Formation Mechanisms in the Large-Scale Variations in Artic Ocean Hydrological Process) contain comprehensive syntheses of Soviet research on Arctic Ocean variability. The first is authored by Doronin (1986) and the second by Nikiforov and Shpayker (1981). The latter contains tabulations and graphics depicting the mass budgets and fluxes

in various Arctic regions, including listings of years for which measurements of regional mass fluxes are available; derived maps of the circulation of the Arctic Ocean at various depths; and cross-correlations (at lags ranging from zero to several years) presented to support postulates about causal mechanisms. The water budget analysis is more comprehensive and substantive than any corresponding large-scale analysis by Western scientists. The text provides sufficient detail to indicate that the 1950's and 1960's are more data-rich than earlier periods. A major conclusion of Nikiforov and Shpayker is that the evolution of large-scale oceanic anomalies is a response to atmospheric forcing and oceanic influxes over seasonal to multiyear periods -- "the oceanic fields ... do not respond strongly even to gross atmospheric circulation anomalies ... whose time duration is less than one season". However, considerable speculation about causal links is present in later sections, e.g., in the attempts to relate SLP forcing to fluctuations in the solar wind. Despite these speculative elements, the two books appear to represent an untapped resource for Arctic researchers in the West. Diagnostic and numerical model studies of interannual variability have not yet fully exploited the data contained in these texts.

Individuals who appear to be spearheading efforts relative to specific regions will now be noted. Timofeev's (1957 and 1962) work on the inflow of North Atlantic water to the Arctic has been continued and expanded by Mandel (1976 and 1978) and Yanes (1976). While Mandel merely computes time series of mass and heat inflow for 1949-1973, Yanes seems to have emerged as the leading Soviet oceanographer on the subject of Arctic/North

Atlantic exchange. The Soviet literature contains frequent citations of Yanes' work on the variability of North Atlantic inflow, the disposition of the North Atlantic heat within the Arctic Basin, and the application of the corresponding data to ice forecasting. For example, Yanes (1976) documents three-to-four-fold changes in the annual Atlantic heat inflow, and claims that this inflow correlates "closely" with Kara Sea ice extent at a 3-year lag. Yanes (1977) presents tables of the annual values of temperature and salinity at different depths of the Faero-Shetland channel. Nikiforov, Shpayker and Yanes (1977) present surveys of Soviet work (through 1977) on the influxes and corresponding vertical heat exchanges attributable to North Atlantic waters. Appel and Gudkovich (1984) discuss the importance of related heat and salinity influxes to the Kara Sea in a recent Soviet assessment of the potential impacts of river diversions.

For the Pacific sector, Shpaikher (deceased) published considerable material on the Bering Strait influxes of mass, heat and salinity, together with analysis of the disposition of these quantities in the Chukchi and East Siberian Seas. Shpaikher and Yankina (1969) conclude from the then-available data that the Bering Sea properties propagate westward across the Chukchi and East Siberian Seas with timescales of 1-2 years. Arikainen (1976) relates the Bering Sea salinity influx to the antecedent SLP field, and claims that the area of the Chukchi flaw lead in June correlates at 0.5-0.6 with the Chukchi Sea salinity measurements of the preceding <u>autumn</u>. The same author, one of the younger AANII scientists, has performed further predictability studies of the Chukchi flaw lead. Blinov and

Vorob'ev (1981) present a more recent synthesis of Soviet measurements of Pacific waters in the Arctic including statistics on the variability of the temperature/depth of the Pacific waters and an explanation of a semi-annual component of that variability.

Specific work of interest to Arctic ice/ocean modelers is the Soviets' construction and analysis of dynamic topographies of the Amerasian sub-basin (bounded by 90°E, 120°W and the pole). Annual fields of dynamic topography for 1949-1973 (25 maps) are presented by Treshnikov et.al. (1976) and the fields are expanded into EOFs. Correlations of the EOF amplitudes with SLP data are claimed to show that the SLP patterns of the preceding two summers (and the preceding fall/winter) determine the annual circulation of the surface waters of the Arctic. Concurrent SLP/topography correlations as large as 0.70 were reported earlier by Bannov-Baikov (1974). The topographic anomalies are also correlated, although less convincingly, with subsequent sea ice conditions (Treshnikov et. al., 1976).

Studies such as the above topographic analyses were made possible by the Soviets' Arctic oceanographic database, which appears to be superior to the corresponding data available to western scientists. In addition to the extensive collection of measurements from drifting ice stations, the Soviets have performed annual oceanographic surveys in March-April of each year through a set of aircraft landings at intervals of 125-300 km (Belyakov et. al., 1984). As claimed by Belyakov et. al., the fields derived from these surveys may well give the "most complete currently existing picture of the year-to-year variability of the circulation in the Arctic Basin".

The data from these annual surveys have been used for the initialization, driving and verification of "state-of-the-art" Soviet model simulations of the Arctic Basin (Belyakov, Volkov, Glazova and Ponomarev, 1984). Ponomarev, who seems to be a leading Soviet modeler of the Arctic Ocean on the basis of frequent literature citations in recent years, provided a diagnostic method of calculating vertical velocities, density redistributions and ocean circulation in the entire Arctic Basin for individual years. The ocean circulation simulated for 1975 (Belyakov et.al., 1984) is quite consistent with the severe ice conditions observed in the Alaskan sector during 1975-76. As noted in the article, this model is diagnostic rather than fully prognostic like the Semtner and Hibler/Bryan models in the U.S.

4. Long-Range Sea Ice Forecasting

Soviet efforts in long-range forecasting of sea ice will be distinguished here according to the numerical modeling and the empirical (statistical) approaches. While the Soviets have published considerably more literature on long-range ice forecasting by both approaches than have Western scientists, the literature contains little specific information on the operational utilization of these forecasts. In the case of the North Atlantic forecasts prepared by the Murmansk branch of the AANII, information on operational utilization may be classified. In the case of the western portion of the Northern Sea Route, where the Soviets claim to have begun year-round navigation in 1980 (Tolstikov, 1982), improved ice reconnaissance seems to be regarded as the most essential factor (TASS, 1985). However, Volkov (1972) claims that Soviet economists' estimates indicate

a gain of 360 navigation days during the 1960's as a result of planning decisions based on ice forecasts. A recent comment by Timokhov and Mustafin (1986) is relevant in this regard: "... the growth of the transport icebreaker fleet is outstripping development of equipment for its hydrometeorological support". It is unclear whether this statement refers to equipment for observing the ice or to equipment for transmitting information between forecast centers and the field.

4a. Numerical Modeling

There is no indication that the Soviets currently employ a large-scale (Arctic Basin) numerical model for real-time ice prediction in the manner in which FNOC utilizes the Hibler/Prellor model. Perhaps because of computing limitations, the Soviets also seem to lag their U.S. counterparts in large-scale sea ice modeling for climatic research. Despite some sophisticated PBL formulations for computing surface air stresses (e.g., Timokhov, 1974), practical applications of the formulations seem minimal. However, as indicated by the following review of focused modeling efforts, and in view of the Soviets' oceanic database described earlier, the gap in basin-scale simulation capabilities may be closing.

Two modeling topics on which the efforts and progress made by the Soviets exceed those of Western modelers are 1) the simulation (prediction) of the autumn freeze-up, and 2) the parameterization of the summer melt. The freeze-up simulations have generally utilized variants of Doronin's (1960; also, Doronin and Sychev, 1974) ice-ocean model containing a multilevel variable-depth mixed layer; salinity effects are

included but ocean currents are "constant". Moskal' (1977) and Appel and Gudkovich (1977) have applied this model to the Barents and East Siberian/Chukchi seas, respectively. Smetannikova and Teitel'baum (1974) show a network of grid points in the Soviet Arctic for which this model is evidently used to produce operational forecasts of freeze-up dates. The model is, however, temperature-driven. Appel and Gudkovich (1977) present a formulation of summer melt (albedo parameterization, lateral vs. bottom melt) that is considerably more sophisticated than the melt formulations used in the Hibler model and in GCM treatments of sea ice. In general, the Soviets seem to lead western researchers in formulating the albedo of sea ice, especially during the melt stages (e.g., Appel and Gudkovich, 1977 and Nikolaeva and Sesterikov, 1976).

Ice model simulations of a large segment of the Soviet Arctic (Kara, East Siberian, Chukchi seas) have been reported by Appel and Gudkovich (1977). The model contains temperature-dependent ice growth rates, constant ocean currents, and a four-force momentum equation with a viscosity term for ice interaction. The latter is said to reduce the computing requirements considerably, thus giving an "indisputable advantage" to the model. This model was run with a two-day timestep for 27 different years (through 1972) for the September-May period, and the output was used to initialize simulations for the subsequent summer periods. Although they do not provide substantive verification statistics, the authors cite the need for better ocean current data and for the improvement of a number of "ad hoc" parameterizations. The need

for improved current measurements north of Alaska and Siberia is also mentioned by Gudkovich and Teitel'baum (1977).

Appel and Gudkovich (1984) have also performed a diagnostic model analysis of the possible changes in the Kara Sea salinity distribution that may arise from river discharge anomalies. These two scientists appear to be at the forefront of Soviet ice modeling efforts directed towards practical applications. Their work, together with the ocean modeling of Ponomarev and colleagues, may have put the Soviets on the brink of useful exploitation of numerical models for operational long-range ice forecasting.

4b. Empirical Strategies

While the Soviets appear to have lagged the West in the operational use of large-scale ice models, they have lead the West in research on empirical forecasting strategies-- certainly in terms of the volume of published results and apparently in terms of the usefulness of these results. Empirical input has been used extensively in the preparation of seasonal forecast for the Gulf of Anadyr, the Chukchi, East Siberian, Laptev, Kara, Barents and Greenland seas, and the Labrador Sea/Davis Strait. Long-range forecasts for the latter three regions were begun in 1971, while the forecasts for the Soviet seas have been prepared since the mid-1940's (Kirillov, 1977).

The empirical procedures used by the Soviets have been developed from a sea ice data base containing two components. The first is the dataset on sea ice in the Soviet Arctic, for which the relatively complete data coverage extends back to 1936 (Zakharov and Strokina, 1978). This dataset has not been made

available to Western researchers. The second component is the data for non-Soviet seas, for which the Soviets have utilized widely available chart series such as the Danish ice yearbooks and the British ice charts for the North Atlantic; Canadian and U.S. charts for the North American Arctic; and, in recent years, imagery from U.S. and other satellites (Kirillov and Khromtsova, 1974). Thus the ice data is available to the Soviets for statistical analyses pertaining to foreign waters is the same--sometimes fragmentary--data available to Western researchers. The Soviets do seem to have exercised care in extracting indices of ice coverage from the non-Soviet data (e.g., Kirillov and Khromtsova's tabulation of Greenland sea ice coverage).

Especially in the last ten years, the published literature contains less detail on Soviet forecasts for their own waters than for non-Soviet waters. Volkov and Zakharov (1977) present a climate-flavored analysis of ice variability in the Soviet Arctic for the period 1945-1975. In an earlier paper, Sancevich (1976) distinguishes the western Soviet Arctic (Barents, Kara seas), where the summer ice anomaly is claimed to depend primarily on the winter ice accumulation, from the eastern Soviet Arctic (East Siberian, western Chukchi seas), where the summer ice anomaly is said to depend primarily on the amount of offshore airflow during May-August. For the latter region, Sancevich claims that solar activity and the "polar tide" can be used to describe 55-70% of the variance of the offshore flow--and hence ice coverage. Volkov and Sleptsov-Shevlevich (1974) analyzed the Soviet summer ice data for 1930-1977 in terms of secular trends and cycles in ten sectors along the northern Soviet coast; cycles of two and seven years were claimed,

together with an eastward "migration" of periods of heavy and light ice. An east-west opposition of anomalies was also claimed. Yanes (1975) claims that the inflow of water through the Faero-Shetland region correlates "closely" (r = -0.637) with ice cover three years later in the northwestern Kara Sea. In a corresponding study of the Pacific sector, Arikainen (1976) reports that the autumn salinity measured at 5-6 Soviet stations correlates at 0.5-0.6 with the area of the Chukchi flaw lead the following June.

While not presenting details of the forecasting techniques for the Soviet Arctic, a survey paper by Volkov (1972) describes the major inputs as correlation statistics such as those above, thermodynamic model calculations of the freeze-up dates, and systematic ice reconnaissance to delineate the boundary between first-year and multi-year ice.

The published procedures for ice forecasts for the non-Soviet Arctic are, almost without exception, empirical. Kirillov (1977) notes that the accuracy of these procedures has been greater for the Atlantic seas than for the Pacific sector. (Results of ice forecasting studies by Western scientists have not shown a similar regional dependence.) For the Greenland Sea region, Kirillov and Khromtsova (1974) present detailed algorithms for predicting the monthly ice cover, May-August, at lead times of 2-6 months. The major predictors are Barentsburg air temperatures and the export of Arctic ice through Fram Strait (computed from pressure differences). The explained variances of 50-60% may be somewhat exaggerated because low correlators (e.g., sunspot numbers) were included as additional predictors. Lebedev and Uralov (1972) discuss predictions for

the same region in terms of air temperatures at several Greenland stations and pressure gradients over nearby regions, although they note that their regression "equations seem useless unless data of the atmospheric pressures in March, April and sometimes May are used". Later work by the same authors (Lebedev and Uralov, 1977) presents regression equations for Greenland Sea ice cover in terms of year-to-year persistence, October-February air temperatures from surrounding stations, and October-February sea surface temperatures (SST's) at two North Atlantic weather ships. Explained fractions of variance are generally 30-60% at lead times of 3-6 months. (The physical mechanism by which SST anomalies influence the ice is claimed to be through their influence on the atmospheric circulation. Western scientists have yet to detect a North Atlantic SST influence that is strong enough to be useful on these timescales.)

<u>NOTE</u>: Work by John E. Walsh and G. Fleming relating Atlantic SST patterns and North Atlantic ice edge conditions have shown meaningful correlation over various lags (See appendix B for additional details).

Predictability studies for the Danish Strait and Labrador Sea regions have been done primarily by scientists at the AANII's Murmansk branch. Nikol'skaya, Senyukov and Kogan (1977) use a 16-year database to derive predictive regressions based on SST data from a set of nine North Atlantic weather ships. Correlations at lead times of one-two seasons are 0.4-0.5, although correlations involving more southerly SST's at one-year lead times are as large as -0.68. Fall-winter air temperatures over land are claimed to correlate at -0.73 with springtime ice in the Danish Strait. (Little correlation was found with Girs'

circulation types.) Kogan et al. (1977) use similar regression parameters for predicting spring-summer ice cover in the Danish Strait at 2-6 month lead times. Kogan and Orlov (1981) later include the intensity of the Icelandic low and the <u>residuals</u> of autoregression model forecasts of ice cover as predictors. (This strategy of using atmospheric and oceanic predictors to improve upon "persistence" is often included in Soviet empirical procedures, and may merit further quantitative evaluation by U.S. forecasters.)

<u>NOTE</u>: This approach of using both oceanic and atmospheric predictors is currently being pursued by the authors.

For the Labrador Sea region, Orlov (1977) uses autocorrelation statistics to argue that the scales of the fluctuations are 200-250 miles and 30-50 days, and that the ice anomalies are carried along by the Labrador Current at 5-6 miles per day. Kogan and Orlov (1981) describe regression equations based on water and air temperatures at five North Atlantic weather ships, air temperatures at three coastal stations, and pressures from the Labrador Sea; "81% skill" is claimed for the forecasts made in September-October, i.e., at 4- to 5-month lead times. Kogan and Orlov also mention a new "dynamical-statistical" method of a Soviet scientist named Alekhin, and claim that grid-point forecasts made by this method are 80-90% reliable.

For the Baffin Bay and Alaskan regions, the most substantive empirical work by the Soviets appears to be that of Smirnov (1979) (See Appendix B for an evaluation of Smirnov's approach). Various regression equations for the May-September ice cover in both regions are presented by Smirnov in terms of

antecedent air temperatures (Barrow), pressure differences along several transects, and ice transport into the Greenland Sea. The equations can be used as early as January. However, the developmental data base is only 14-16 years, implying that considerably more data now exists than was used by Smirnov. Smirnov (1980) also claims to have detected an "opposition" of summer ice severity in the Baffin Bay and Alaskan areas.

Nearly all the published Soviet work on empirical sea ice forecasting seems to have been done in a non-automated mode, i.e., without exploiting computer capabilities. Gudkovich (1981) comments that the Soviets plan "... in the very near future ... a transfer to the computer of very laborious searches for optimal predictors and construction of prognostic equations". Thus it is quite possible that the empirical prediction techniques described here will soon be superseded by more sophisticated procedures.

NOTE: Following the basic survey of pre-1980 Soviet material, post 1980 material was found to indicate a rapid transfer to computer procedures.

5. Observational Programs

A key component of the Soviet system of ice forecasting is their program of systematic surveys and other observations of sea ice, ocean and atmospheric variability in the Arctic. The annual springtime oceanographic surveys noted in Section II have provided the Soviets with a data base that can provide considerable advantage in diagnostic and modeling studies of large-scale ice-ocean coupling. These surveys are said to cover most of the Arctic Basin at grid intervals of 125-300 km (Belyakov et al., 1984). On the basis of the mass and salinity budget analyses

described earlier, longer records of salinity temperature density (STD) sections evidently exist for various inflow regions.

Weather and ocean information is also transmitted 12 times per day from the Soviet NP drifting stations, of which there has been generally two, but currently three, in operation. These are supplemented by automatic stations, patrol ships and jumping teams (Tolstitov, 1982), presumably on a less regular basis. Terziev (1977) claims that the three "expedition vessels" of the AANII's Murmansk branch survey 35,000-40,000 miles each year in the northern seas and the North Atlantic, servicing more than 1500 buoys and irregular stations.

Ice reconnaissance has been described as an "indispensable part" of operational navigation of the Northern Sea Route. The January aircraft surveys of over 10,000 km, Murmansk to Uelen, are said to be used for both short-term and long-term forecasts. An "airborne facsimile sender" is carried on these surveys; on-board data storage devices are also used (Murlin, 1985). Aircraft include two IL-14's and, in the near future, an AN-74 aircraft capable of landing on ice (TASS, 1985).

Key aircraft instrumentation includes the "Toros" side-looking radar, radar ice thickness gauges, IR radiometers, laser altimeters, and aerial cameras. A recently-developed "Led-2" (radar) instrument is said to measure ice thickness from aircraft, and to identify cracks and channels even if those features are obscured by new ice or snow. The value of these instruments to the Soviets may be indicated by the fact that the 1984 USSR State Prize was given to the five scientists who

developed the radar instrumentation for the ice thickness measurements (Pravada, 1985).

Little published material has appeared on the use of satellite imagery by the Soviets for ice reconnaissance and forecasting. While such information may be classified, there is no indication that the Soviets are pursuing satellite microwave sensing applications (e.g., first-year vs. multi-year mapping) as strongly as are Western scientists.

NOTE: The number of articles on the utilization of satellite data for ice conditions increases rapidly following the COSMOS Satellite launches which carried infrared, microwave, and SLR sensors.

The literature does contain preliminary information on an automated "tracking and forecasting" system for sea ice--ALISA --which was "to be carried out during the tenth 5-year plan", beginning in 1975. This system includes a changeover from visually-based to instrumental modes of data collection, a computational and forecasting subsystem (CFSS), and an automated system of product dissemination (Bushuyev, Volkov, Gudkovich, Novikov and Prokof'yev, 1977). Progress in the implementation of this system is not apparent in the literature reviewed in detail to date. However, without referring explicitly to ALISA, Timokhov and Nikiforov (1981) do outline a schematic system for operational Arctic ice/ocean/atmosphere forecasting (specifically for shipping). Elements of "control theory" can be detected in this system, which appears to be somewhat ambitious relative to the published material on Soviet ice forecasting. These Soviet authors, both of whom are "veterans" of ice research at the AANII, note that "the traditional criterion of efficiency of a forecasting method is not

adequate". As in the case of ALISA, no follow-up description of the implementation or use of the outlined system has been found in the translated literature.

CONCLUSIONS AND RECOMMENDATIONS

The Soviet literature indicates an accelerating shift from the investigation of cyclic solar and earth orbital factors as the forces causing atmospheric, oceanic, and ice condition changes to study of the reactions due to internal forces of atmospheric, oceanic, and ice patterns. Rapid advances were made in the 1980's in the use of satellite data and computers in environmental modeling (See Appendix C part 1). To date their emphasis remains on regional and local analytical modeling efforts. Their extensive data base in their home portions of the Arctic Ocean, coupled with their progress in remote sensing and computer processing and historical archives of analytical models, provides them with the ingredients for significant breakthroughs in Arctic environmental condition prediction.

The following four items address significant changes in the Soviet approaches that were noted by the authors in the post 1980 literature as compared to the pre-1980 literature. These four points were annotated in the preceding text.

1. The comment (pages 23-24) that Western scientists have yet to detect a North Atlantic SST influence on ice edge conditions with lead times of 3-6 months or more, as shown by Lebedev and Uralov, has been overtaken by events. Walsh, in the evaluation of Lebedev and Uralov's regression equations, as well as with independently derived equations from a U.S. data base, has found similar relationships. Also, Fleming (1987) found correlations of North Atlantic SST anomalies and ice conditions over various lags.

2. The statement "The strategy of using atmospheric and oceanic predictors to improve upon 'persistence' is often included in Soviet empirical procedure, and may merit further quantitative evaluation by U.S. forecasters.", made by the authors (page 25) has been overtaken by their current efforts and plans for combining SST and large scale atmospheric anomalies in correlation studies with ice conditions.

3. The statement "Nearly all published Soviet work on empirical sea ice forecasting seems to have been done in a non-automated mode, i.e., without exploiting computer capabilities.", (page 26) does not apply after about 1980. The literature of the mid 80's indicates a rapid increase in computer usage.

4. The statement "Little published material has appeared on the use of satellite imagery by the Soviets for ice reconnaissance and forecasting.", (page 27) is also invalid after about 1980. Later references indicate an increasing use of satellite imagery and other data. The early emphasis, however, appears to have been on oceanographic and atmospheric conditions with interest in application of infrared (IR), microwave, and side looking radar (SLR) sensors to ice conditions steadily increasing during the 1980's. This increase in the number of articles on IR, SLR, and microwave data usage parallels the launches of COSMOS satellites which were designed for support of oceanographic research. The increase in use of COSMOS data relative to the Arctic coincides with the general growing interest in the Arctic as an operational area. The following partial list of COSMOS satellites with sensors pertinent to ice condition determination indicates the probable

continued increase in ice condition sensing capabilities and related research.

COSMOS #	Launch Date	Sensors
1076	02/79	IR/MICROWAVE
1151	12/80	IR/MICROWAVE
1500	09/83	SLR/IR/MICROWAVE
1602	09/84	SLR/IR/MICROWAVE
1766	07/86	SLR/IR/MICROWAVE

A number of the Soviet articles obtained late in the project have not been studied to the degree of the earlier ones. Therefore there are no detailed findings to offer on them at this time. Appendix A provides brief statements on some of the recent pertinent articles. The author is of the opinion that rapid and significant improvements have been made in the last few years and will continue into the near future in Soviet capabilities in Arctic forecasting. These recent and evolving capabilities and procedures are of prime interest to U.S. scientific communities.

This survey and study provide background insights and knowledge leading up to the rapid changes in the main theme of Soviet long-range forecasting and application of satellite data and computer technology. However, we have only gained a "peek" at the current capabilities and projected near-future developments. Because of the Soviets' historical routine involvement with Arctic living and operating problems they have likely developed forecast techniques for a broad array of high latitude environmental conditions. In addition to long-range ice forecasting, their approaches/techniques of general weather condition forecasting should be surveyed. The question of whether we had reviewed the Soviet weather forecasting methods

for Arctic conditions was asked of the author by Captain D. Sokol, Atlantic Fleet Meteorologist, at the recent 1987 U.S. Navy Symposium on Arctic Cold Weather Operational Support for Surface Ships. A question posed by both Dr. P. Twitchell of ONR, at the cold weather symposium, and earlier by a member of the Oceanographer of the Navy's staff, was how our Arctic research effort fits into the Navy's Arctic research program. Specifically, how it related to the Navy Environmental Prediction and Research Facility (NEPRF) Arctic program. The ONR/NEPRF Arctic programs are generally focused on ASW and/or Marginal Ice Zone Condition Exercise research. The long-range ice forecasting and general weather forecasting problems have not received much attention. By extracting useful information from the Soviets knowledge/data base we can offer a relatively inexpensive solution to the ice/weather forecasting problems.

It is recommended that the following efforts be pursued. First, continue the survey of Soviet literature in order to more thoroughly investigate and evaluate the recent Soviet long-range ice forecast approaches. Second, expand the survey subject material to include weather forecasting in order to provide to the general U.S. Navy Arctic research and development program unique and/or useful Soviet methods of weather forecasting. The following specific recommendations are made:

<u>Relative to long-range ice forecasting</u>

1. The evolution of combined numerical and empirical modeling efforts and applications. The combined approach is only recently gaining support in U.S. efforts.

2. Comparison of Soviet and U.S. utilization of satellite data (side looking radar, microwave, and infrared). The Soviet's more practical approach to operational problems may provide us with extremely important in situ models which could be incorporated into the U.S. Navy's Technical Environmental Shipboard System (TESS) which is currently being developed at NEPRF and other Navy laboratories.

3. The recognition and utilization of the varying spatial ice condition responses within the Arctic to changing atmospheric circulation patterns and Fram Strait ice outflow. This concept has great potential in improving the understanding of atmospheric, oceanographic, and cryospheric climate interactions.

4. The application of combined atmospheric and oceanic forcing factors to ice condition responses. A thorough review of the recent texts by Doronin (1986) and Nikiforov and Shpayker (1981) should be made. This approach has the potential of improving long-range ice forecasting by providing information on scales of variances that are independent from direct atmospheric forcing.

5. The level of emphasis on large scale versus regional and local modeling of ice conditions. The regional and local modeling efforts should be closely monitored for potential use by U.S. Arctic forecasters. A high level of interest in specific

regional area forecasting exists at the Naval Polar Oceanography Center (NPOC), but the Navy's numerical models are global in design.

6. Monitor changes in policy from deploying resources to the field sites to one of centralized support using hemispheric models, an indication that they have acquired adequate computer power to handle hemispheric models. When the Soviets acquire adequate computer power for hemispheric/global models it will be very interesting to see if they revert to the Western approach of large scale modeling or continue their regional approaches.
7. Evidence of the use of computers in empirical forecast models with the extensive Soviet data bases and possible breakthroughs in understanding of basic atmosphere, ocean, ice condition relationships.
8. Evaluation of Soviet models in areas where they appear to lead Western efforts, such as autumn freeze-up and summer melt.

<u>Relative to general weather forecasting</u>

9. Extension of the literature review to include general weather forecasting for the Arctic region. Evaluate Soviet techniques that appear to be unique in approach and offer potential gains to the U.S. forecast program. Provide such findings to ONR and/or NEPRF for consideration for use in their Arctic programs.

Our limited review of the most recent Soviet literature indicates they are in a period of rapid development in forecasting methods. This initial effort has provided a necessary level of background information against which current Soviet as well as Western methodologies can be compared. An understanding of the approaches the Soviets take in applying new computer and satellite technology, in combination with their prior methods, will likely contain the most significant new information relative to breakthroughs and/or unique methods that could be utilized by our forces.

Our recommendation is for the continued survey of the most recently available Soviet literature on long-range ice forecasting plus general weather forecasts and evaluation of selected models. The end results will be toward identification of unique Soviet work as well as those methods that should be transferred into the U.S. Arctic program.

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[1] JPRS--U.S. Joint Publication Research Service

[2] FTD-- Foreign Technology Division

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APPENDIX A

Recent Soviet Articles on Hydrometeorology

by

Ronald E. Englebretson

November 1987

Drifting Ice Stations

JPRS[1] 13 Nov 1985

MOSCOW TASS 13 May 1985, pg. 41, In English.

New 38 man crews on NP-26 and NP-27 (19 on each apparently). Replaced by plane. Collecting ocean/atmosphere data and transmitting 12 times a day (2 hourly obs).

NP-26 functioning since May 1983. Now near "pole of inaccessibility" - area most distant from all continents. Only one other Soviet station was there in 1970's. Floe has moved little in last three months.

NP-27 opened two years ago. Now on its way to the geographic North Pole and in 12 to 18 months it is expected to be carried to the Greenland Sea area.

[1] U.S. Joint Publications Research Service

JPRS 16 Aug 1985

Yerevan KOMMUNIST 14 May 1985, Leningrad release.

New teams on Arctic drifting stations. 3rd team on NP-26 under N. Blinov. Station started 3 years ago

north of Wrangel Island, is now near pole of relative inaccessibility with little movement for 3 months. NP-27 mean while has drifted to northwest of New Siberian Islands and is expected to eventually be carried out to the Greenland Sea.

NOTE: Ocean Science News, 12 May 1987

Soviet Nuclear Icebreaker rescues researchers off NP-27 as station drifts into Greenland Sea. Breaker made a 1500 n mi trip across the Arctic.

JPRS 31 Mar 86

Moscow IZVESTIYA

A. Ryabushev, Leningrad 29 Nov 85

USSR State Committee on Hydrometeorology and Monitoring of National Environment and The Central Committee on the All-Union Leninist Communist Youth League (KOMSOMOL), have decided to create a third KOMSOMOL drifting scientific research station: Severnyy Polyus - 28 (SP-28)

Observations will be extensively automated, said Nikolay Aleksandrovich Kornilov, deputy director of Arctic and Antarctic Scientific Research Institution. Long term agreement regarding development of automated complexes and introduction to drifting stations concluded with Leningrad Polytechnic Institute to create:

Automatic post for receiving and transmitting satellite information on ice conditions.

The compilation and facsimile transmitting of a map of ice condition of the <u>entire</u> Arctic basin well be done with the aid of a computer for the first time at a drifting station.

Station manning scheduled winter of 85/86 (see next article).

<u>Comment</u>: Level of USSR interest/involvement indicated by establishment of 3rd drifting research camp and installation of high technology satellite receiving station.

JPRS 31 Mar 86

Moscow SOVETSKAYA ROSSIYA

Article of 28 Dec 85. I. Podshivalov.

SP-28 will begin operation next spring (April 1986). For the first time a minicomputer will be used at a drifting ice floe camp.

Meteorology, oceanography, ice research group, aerologists, satellite information recovery, climate, ocean-pollution monitoring projects will be conducted.

Currently searching for a suitable ice floe. COSMOS - 1500 satellite being used in search.

<u>Comment</u>: Example of use of satellite imagery. However, a little surprising that they don't have ready information on suitable floes.

JPRS - 22 July 1986.

KRASNAYA ZVEZDA 11 Apr 86 Article

Plans for Arctic parachute expedition for dropping personnel and cargo. Involves, 40 parachutists plus equipment onto drifting ice flow where Arctic station SP - 28 is to be organized. Located at 78°42'N 168°55'E. Similar operation carried out in 1984:

14 parachutists plus fuel and equipment including a tractor. Dropped to help crews at SP-26 and SP-27. Work at SP-28 to include making a runway for light aircraft.

Comments: Air drop experience of USSR significantly greater then US. Drop of 1984 was to assist manned camps, planned drop of 1986 appears to be for initial manning and station construction.

JPRS 22 May 1987

MOSCOW SOTSIALISTICHESKAYA INDUSTRIYA 12 Nov 86

Emergency air drop procedures tested at drifting stations SP-27 and SP-28. Drops included two "DT-75" tractors and four cargo platforms of 160 drums each of diesel fuel and 24 sports parachutists of the All-Union Volunteer Society for Assistance to the Army, Air Force, and Navy. SP-27 was reported to be 600 x 700 meters, 5-6 meters thick and about 200

kilometers from the geographical North Pole in the fall of 1986.

MOSCOW SOTSIALISTICHESKAYA INDUSTRIYA 17 Dec 86

IL-76 to drop cargo by parachute after "SP-28" ice floe splits. As crew was preparing ice runway, floe split with a "terrible cracking" sound on night of 9-10 Nov. Original size had been about 1 kilometer wide and a little longer, now split into two parts with no chance of landing aircraft. While earlier practice airdrops had been made, air crews would now have to make drops in the dark of the polar night. "A few days earlier an IL-14 had dropped several drums without parachutes and unfortunately not all had hit their mark." An IL-76 aircraft will make several trips out of Tiksi carrying about 60 tons per trip.

Comment: Ultimate success/failure of operation unknown at this time by author. Apparently routine resupply by ski equipped small aircraft would have been conducted during polar night if runway had been available.

Satellite Data and Systems

JPRS - 13 Jan 86 Manuscript 160 pp., Received 16 Nov 83.

Likhachev, I. V. and Michurin, A. V. Leningrad State University.

Limitation of using satellite information (SI) such as IR received in remote regions for scientific study.

Discussed use of magnetic tape for SI recording and saving of data for later use by researchers.

<u>Comment</u>: Same problem U.S. has. Operationally received local area coverage satellite imagery frequently does not get into the official archives, and therefore is not available to researchers.

JPRS - 24 Jan 86

Mar-Apr 85 Article, Received 28 Dec 83.

V. YU. Aleksandrov, A. V. Bushayev, V. S. Loshchelov of Arctic and Antarctic Scientific Institute, Leningrad.

Determining the Solidity of Sea Ice from Aerospace Images from ISZ's (artificial Earth satellite).

Used computer facilities at:

State Scientific Research Center for the Study of <u>Natural Resources</u>, to solve the problem of automating the processing of images of sea ice through utilization of:

- image input devices
- minicomputer
- video display
- set of processing and output programs/devices

System works in interactive mode with a pen light to distinguish zones with different solidity levels.

Also objective method - produces graphic output of different ice coverage - can be transmitted by facsimile.

Comment: Approach based on image interpretation, implies likely computer enhancement capabilities.

JPRS 13 Nov 1985

Moscow VODNYY TRANSPORT 25 Jun 85, pg. 1.

Shipboard Complex Processes Information from Weather Satellite.

A hardware-software system developed at the Far East Research Center's Institute of Automation and Control Processes has automated the processing of information received on scientific research ships from weather satellites. Also receives readings from many sensing devices.

Comment: System apparently is an R&D/Scientific system, not likely to be readily useable by operational forces.

Aircraft Reconnaissance

JPRS 16 Aug 1985.

Leningrad Feb 1985.

Quantitative aspects of aerial thermal sensing, "equipment with detectable temperature difference of 0.2 - 0.3°K under typical conditions ensures determination of differences in ice thickness of approximately 0.2m (about 6 inches)."

Includes comments on problem of snow cover. Expression utilized to evaluate the influence of different factors on the reliability of ice reconnaissance remotely sensed data.

Comment: Indicates their use of field programs to provide ground truth for evaluation of sensors.

JPRS 16 Aug 1985

VOZDUSHNYY TRANSPORT Moscow 14 May 1985.

AIRBORNE FACSIMILE SENDER USED FOR RECONNAISSANCE.

I. Serebrennikov, senior engineer hydrologist of AANII's department for improvement of the system and methods of ice observation. AN-24 airplane, route Murmansk to Uelen instrumented with special equipment: "Ladoga" facsimile sender, hydrologists conduct visual and instrument aerial surveying. Main purpose, "data collection for computer processing" for use in both short-term and long-term forecasts for shipping routes.

JPRS - 19 Feb 86

TASS 23 Aug 85, pg. 58.

Specialists of the Soviet Ice Recon Service. Conducting strategic survey of the Soviet Arctic Sector, will fly over 5 million sq km of the Eurasian coast to central polar basin area.

Two (2) specially equipped IL-14 planes available. Will draw up maps of ice distribution and forecast probable conditions for Autumn navigation along Northern Sea Route - Northern European ports to Pacific Ocean. Will fly "hundreds of hours" by end of month and drop mail to polar explorers on drifting station NP-26 and NP-27. "Ice reconnaissance has become indispensable part of Arctic exploration and navigation".

Comment: Implies they still rely heavily on basic aircraft reconnaissance therefore neither forecast model output or satellite derived date provide support needed.

Hydrologists: have developed a method of accurate measurement from the plane of:

Strength

Age

State of ice cover.

Ice recon planes fly close cover for convoys and direct helicopter flights off ice breakers.

Recon support ensured success of voyage of "Arkika" nuclear ice breaker to North Pole in August 77. Plus helped pilot out dozens of ships caught in heavy ice off Chukotha coast 2 years ago (1983) - and made it possible to start nearly year-round navigation in the Kara Sea.

A new multi-purpose plane (AN-74) with wheel or ski take-off capabilities will soon be in service. The

plane is designed to take off/land from/on drifting ice floes.

<u>Comment</u>: Intended use for on/off <u>ice floes</u> implies relatively small aircraft, more like a Twin Otter than a C-130.

JPRS 7 May 1986

MOSKOVSKIY KOMSOMOLSVS 2 Feb 86, O. Milyukhov, Correspondent, pg 59.

KA-32 helicopter designed for ice reconnaissance, servicing drilling platforms, and work in mountains. Developed at Design Bureau, Serpgey Nukheyev.

Can carry 5 tons on outside sling

Last year accompanied ice breaker Sibir on cruise over the Northern Sea Route with a ship convoy.

Pilot stressed "all-weather capability". Flew during polar night at temperatures from 0 to -32°C, in blizzards and snowstorms. Operated out to ranges of 250-300 km from ice breaker, found way back at time of visibility restrictions down to 40 to 400 meters. Landed on deck of icebreaker which was towing another ship. Has "complete piloting and navigation set" with back-ups.

<u>Comment</u>: USSR Stress on systems with Arctic region capabilities.

JPRS 7 May 1986

IZVESTIYA 16 Feb 86, pg. 57.

AN-74 airplane in final phase of plant trials.

Intended for transport work in central Arctic basin.

Designed with small gallery, 12 passenger seats, plus cargo compartment.

Two D-36 turbofan engines

6.5 tons of thrust

Tested in extreme temperatures

High temperature of Ashkhabad and

-58° in Verkhoyansk

Consider minus 40-55° as ordinary working temperatures. "Test pilot Yuriy Vlademerovich Kurlin dreams of landing the airplane on drifting ice".

Comment: Two engine aircraft, significantly smaller than US C-130's. As of 16 Feb 86 plane had not been tested on open field (ice floe) landings. Temperature scale of celsius or fahrenheit not indicated but celsius used elsewhere.

Ships and Shipboard Instrumentation

JPRS-10 Jan 86

7 Sept 85 Radio Report, pg. 16.

Candidate of Geographic Sciences A. Lebedev. On ship in Kara and Laplev Sea's. Research supporting merchant shipping along northern sea route.

JPRS 19 Feb 86

Pg. 62.

"Otto Shmidt" flagship of Soviet Arctic research fleet. First scientific research icebreaker launched 5 years ago (1980). Has lab for preserving ice cores, studying life span of ice.

Comment: No comparable USA capability.

JPRS - 10 Sept 1986

VODNYY TRANSPORT 22 May 86.

By: L. Timokhov, secretary of the Communist Party committee of the Arctic and Antarctic Scientific Research Institute, and N. Mustafin, head of a department of the institute (USSR State Prize laureate).

Proposal for advancement of year-round Arctic shipping.

Comments: Points out problems of obtaining cooperation between ministry of: Merchant Fleet, Civil Aviation, Aviation Industry, and Shipbuilding Industry. Also complained of inaction on AANII proposals of 1983 on similar efforts. The need for an interindustry information system and creation of an intersector scientific-technical complex called "Artika" for purpose of

coordinating work on "mastering year-round shipping over the entire Northern Sea Route and ..." implies year-round shipping is not yet a routine operation.

__Forecasting__

JPRS 22 July 1986.

Article 30 Dec 85.

Interview of Aleksandr Aleksandrovich Vasilyev, Director of the USSR Hydrometeorological Scientific Research Center.

Comments on weather monitoring and forecasting methods that are now in use. Progress in heightening the accuracy of forecasts, and work aimed at improving long-term forecasting.

Noted that weather service is one of country's most active user of computer technology. Claims 65% reliability for one month forecasts.

__Comments__: Sounds like PR, verification criteria not mentioned.

JPRS 7 May 1986.

28 Sep 86 Moscow GUDOK No. 50 pg. 4.

Professor G. Ivanov-Kholodnyy. Associate of the Institute of Applied Geophysics.

Comments on How Solar Activity May Affect Weather.

"Colleagues at main geophysical observatory

(Leningrad) have discovered a connection between extreme weather phenomena and periods of solar activity. This applies particularly to droughts: 22 year and 11 year cycles were found."

Books

JPRS 9 Apr 86

Book - 17 July 84, D.M. Sonechkin, (780 copies) 280 pp. Stochasticity in Models of General Atmosphere Circulation. To be used in dealing with numerical and statistical methods and long range local forecast problems.

Comment: Illustrates blend of dynamic and statistical modeling, this approach has little support/interest by USA scientists which tend to lock in on pure dynamic modeling. Maybe largely a status problem among USA scientists while USSR scientists have taken problematic approach.

JPRS 18 Oct 1985.

Book (Collection of works) - Numerical Experiments on Dynamics of Global Climate, Edited by: V. Ya. Sergin and V. I. Shuprynin.

Chapter on Numerical Experiments on Reproduction of

Annual Course of Sea Ice Characteristics in Arctic. By V. M. Karpets.

Comment: Only chapter titles provided; work was done at Vladivostok. Karpets is a new name to this review.

JPRS 8 Oct 1986.

Regional Oceanology, Book by Yuriy Petrovich Doronin.

Includes section on "The Ice Cover" p. 276-282 which Seas freeze-up first, shore ice, polynyas, comments on sea depths, summer layer, and marine synoptic patterns.

Comment: Information source for U. S. Arctic environmentalists/ice forecasters.

APPENDIX B

Results of the Evaluation of Soviet Empirical Models

PART 1

Lebedov and Uralov Model for the Greenland Sea,

Evaluation by Gordon Fleming and John E. Walsh

PART 2

Smirnov Model for Alaskan Area Ice Conditions,

Evaluation by Ronald E. Englebretson

RESULTS OF EVALUATION OF SOVIET EMPIRICAL MODELS

Introduction

This two part appendix contains discussions of the evaluation of Soviet regression equation models for forecasting ice conditions; Part 1 for Lebedev and Uralov (1977) in the Greenland Sea area and Part 2 for Smirnov (1979) in the Alaskan sector of the Arctic. Included in each discussion are figures showing the comparison of the correlations obtained from the Soviet regression coefficients and from the U.S. derived coefficients, plus evaluation comments, discussion of the utility and uniqueness of these approaches, and copies of the translated articles. The discussion of Lebedev and Uralov (Part 1) is a draft version of a chapter from Gordon Fleming's thesis (Naval Postgraduate School, 1987). Readers are referred to the thesis for the final version.

PART 1

Evaluation of Lebedev's and Uralov's Greenland Sea Forecast Model

Assessment of Soviet Skill. (This materical is taken from Fleming (1987), specifically a draft of his section IV.)

Soviet efforts at forecasting North Atlantic sea ice conditions appear to have increased substantially during the 1970's. The translated unclassified literature contains methodologies and results for the Labrador Sea and the Danish Strait produced from various studies done at the Murmansk branch of the Arctic and Antarctic Institute (e.g. Nikol'skaya, et al., 1977, Orlov, 1977). Results for the Danish Strait and Greenland Sea have been reported by Kirillov and Khromtsova (1972), Kogan and Orlov (1981) and Lebedev and Uralov (1977). Although the studies cited above are based exclusively on empirical techniques, thermodynamic budget computations have also been used in other studies, (e.g. Moskal, 1977) as the basis for long-range predictions of freeze-up dates in the Barents Sea.

With respect to ice forecasting efforts by the Western nations, the Soviets appear to have explored more thoroughly the use of statistical techniques for long-range ice forecasting, especially as regards the use of SST data. Kirillov (1977) states that the Soviet's empirical procedures have been more successful for the Atlantic seas than for the Pacific seas. The

more limited studies of ice forecasting skill by western scientists (Kelly, 1979; Walsh and Sater, 1981) do not indicate a similar regional dependence.

Because the Soviets claim considerable skill in seasonal sea ice forecasts that use SST data as a predictor input, it was felt that tests of their forecast procedures would provide a useful benchmark for the results obtained in this analysis. Accordingly, the Greenland Sea ice forecast procedures of Lebedev and Uralov (1977) were tested using the data sets described in Chapter 3 of Fleming (1987). These procedures permit predictions of Greenland Sea ice coverage for April through August in terms of land station air temperatures for October-February, SST gradients for October-February, and the ice cover of the previous August. Separate equations for seven latitude zones and for each of the five months were derived by the Soviets using multilinear regression. The use of 7 x 5 sets of regression parameters increases the likelihood of sampling error, as the data base used by the Soviets was only 15 years (1958-1972) for two of the regions and 25 years for the other regions. The 25 year period used in this study for testing the results was 1955-1979, inclusive. This period was chosen in order to mesh with the SST/ice analysis of the present work.

The air temperatures used by the Soviets were for land surface stations in the general vicinity of the Greenland Sea: Fjord Radio, Jan Mayen Island, Cape Tobin, Medvezhii Island, and Reykjavik. Temperatures averaged over different combinations of these stations were used for different latitude zones. The SST index, which is similar to that used in earlier studies of the North Atlantic (e.g., Lebedev and Uralov, 1976), is the gradient

or difference of SST between two pairs of Ocean Weather Ships. Specifically, the average of the SST's for Ships A and C is subtracted from the average for Ships I and J (Figure 4.1). The physical basis of the index, as presented by Lebedev and Uralov (1977), is an apparent "indirect association" between SST and sea ice. The authors argue that a stronger-than-normal SST gradient in the region shown in Figure 4.1 favors cyclone trajectories from the Danish Strait northeastward towards Spitsbergen, favoring easterly winds and reduced ice cover in the Greenland Sea. Weaker-than-normal SST gradients favor more eastward cyclone trajectories across southern Iceland to northern Norway, favoring northerly winds and increased ice cover over the Greenland Sea. The authors further stat that in the latter case, the SST's close to the MIZ are likely to be warmer than normal, despite the postulated dynamical tendency for above-normal ice coverage.

Because the SST and air temperature predictors are averaged over the October-February period preceding the spring/summer being forecast, the "lead time" of the forecasts is 2-6 months. The procedure does not require forecasts of atmospheric variables. (Lebedev and Uralov claim that the SST/cyclone association is largely absent during the spring/summer months).

The Soviet regression equations (5 months x 7 latitudinal sectors) were tested in several ways:

1. Forecasts were computer using the regression equations exactly as listed by the Soviets, but using SEIC and COADS data as the Soviet data was not available;

2. Forecasts were computed using the Soviet predictors but with the regression constants re-derived from COADS and SEIC data; and

3. Forecast skill was evaluated separately for the 1955-79 and 1958-72 periods.

The results for three of the seven regions are shown in Figures 4.2 to 4.4 in terms of overall correlation coefficients (predicted vs. observed) for the two periods. The following general conclusions are apparent from these figures:

1. Considerable skill is present in nearly all cases, both in forecasts based on the Soviet regression constants and in forecasts based on the re-derived constants;

2. In most cases the recomputation of the regression constants produced modest enhancements of skill over the values obtained directly from the Soviet equations; and

3. The skill obtained using the SEIC and COADS data and Soviet predictors, even with re-derived regression constants is generally 5% or more lower for nearly all cases than that listed by the Soviets.

The average correlation for all plotted data points in Figure 4.2 is 0.73 for the published Soviet claims, 0.59 for the forecasts based on the re-derived regression constants and 0.43 for the forecasts based on the Soviet regression constants.

The partial correlations between the observed ice coverage and the individual predictors are shown in Figure 4.5. While there is some scatter among the various regions and months, several conclusions can again be drawn:

1. The persistence predictor (ice cover of the previous August) is generally the weakest of the three correlators. In no case does the correlation based on this predictor exceed the 95% significance level;
2. The surface air temperature is the highest individual correlator in the early portion of the predicted season (April and sometimes May); and
3. The SST predictor is generally the highest correlator in the latter half of the ice season (June - August).

Of the results gleaned from the Soviet skill assessment, the most pertinent to the present work are that SST input does enhance the seasonal predictability of the Greenland Sea ice coverage, and that the correlation between winter SST and summer ice coverage is statistically significant. Findings such as these have not been reported in the Western literature. The additional observations that the skill levels reported by the soviets are significantly better than those achieved in this study suggests that predictor selection, whether the result of explicit or implicit screening, has introduced some sampling bias. This cannot be tested quantitatively without additional information on the data used by the Soviets, especially the source of their ice data. Differences in the ice data may have contributed to the discrepancies between the two sets of

forecast statistics. Nevertheless, the confirmation of the SST/ice association in the Soviet results provides perspective for the more general SST/ice analyses described (Fleming, 1987).

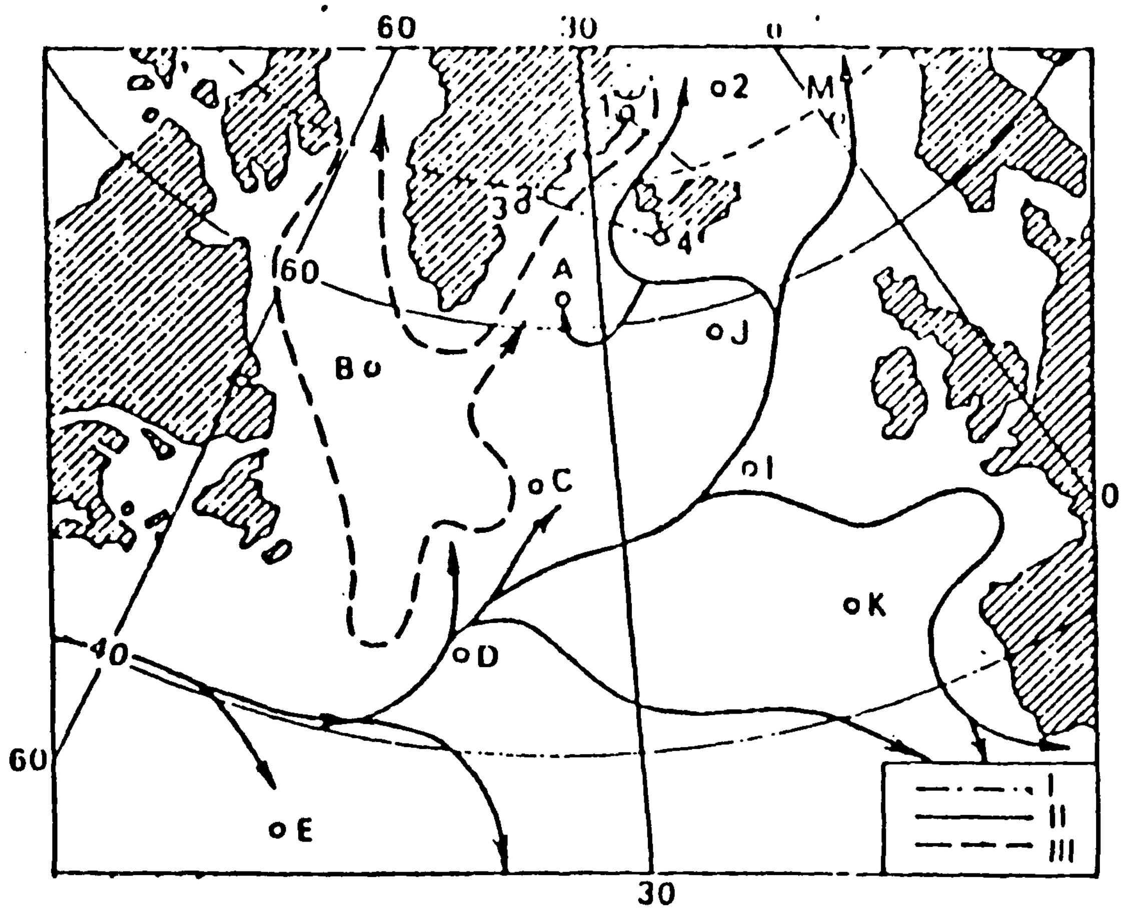

Figure 4.1 Region of study for the Soviet ice cover prediction method. Ocean stations are labelled by letter. Solid arrows are average warm currents and dashed arrows are average cold currents. The numbered positions are meteorological stations: 1-Cape Tobin; 2-Iceland Sea; 3-Angagssalik; 4-Reykjavik [from Nikol'skaya et al. (1977)].

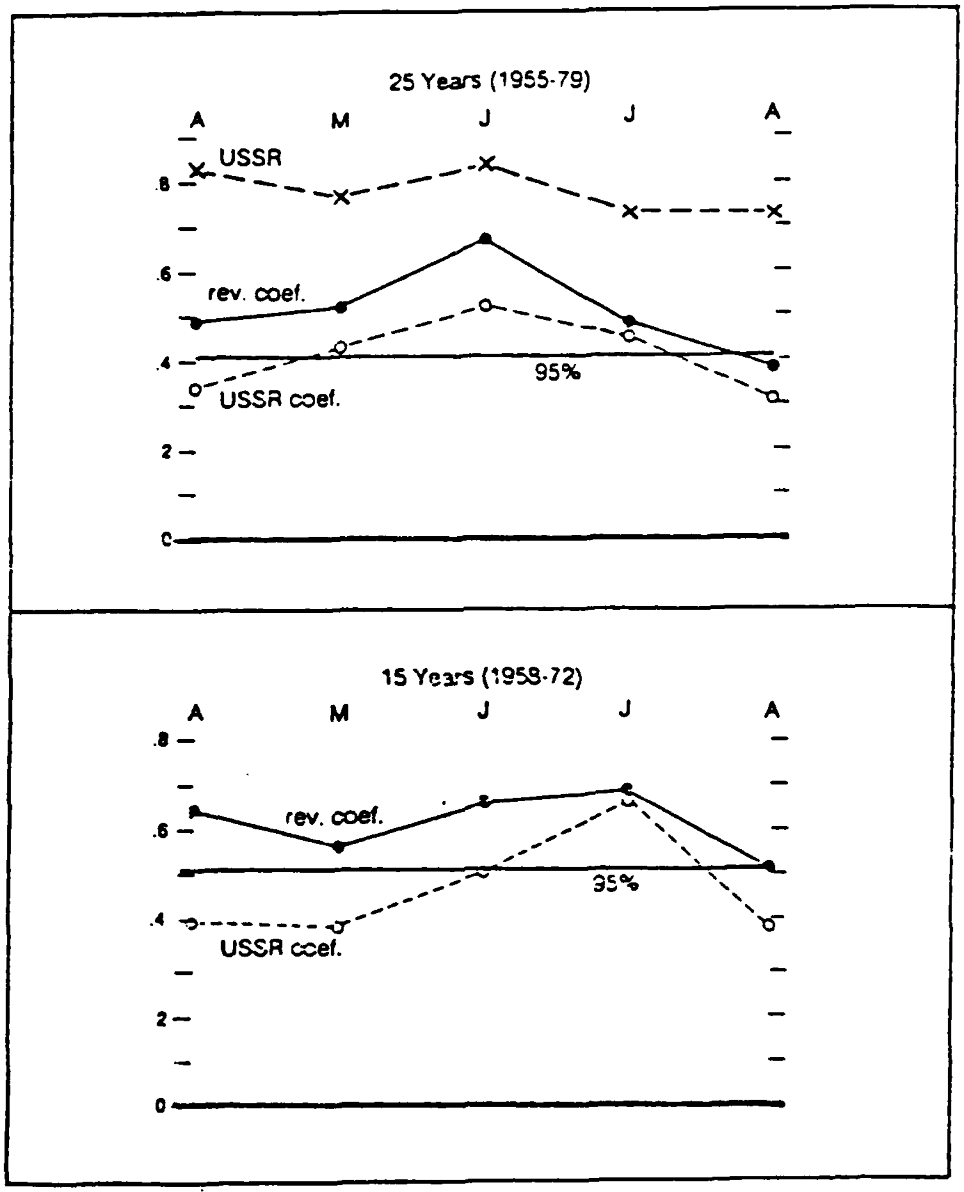

Figure 4.2 Comparison of Soviet correlations (USSR) with correlations calculated using our data and Soviet regression constants (USSR coef.) and our data with recalculated regression constants (rev. coef.). The same variables are used in all three cases. This figure shows values for the Greenland Sea.

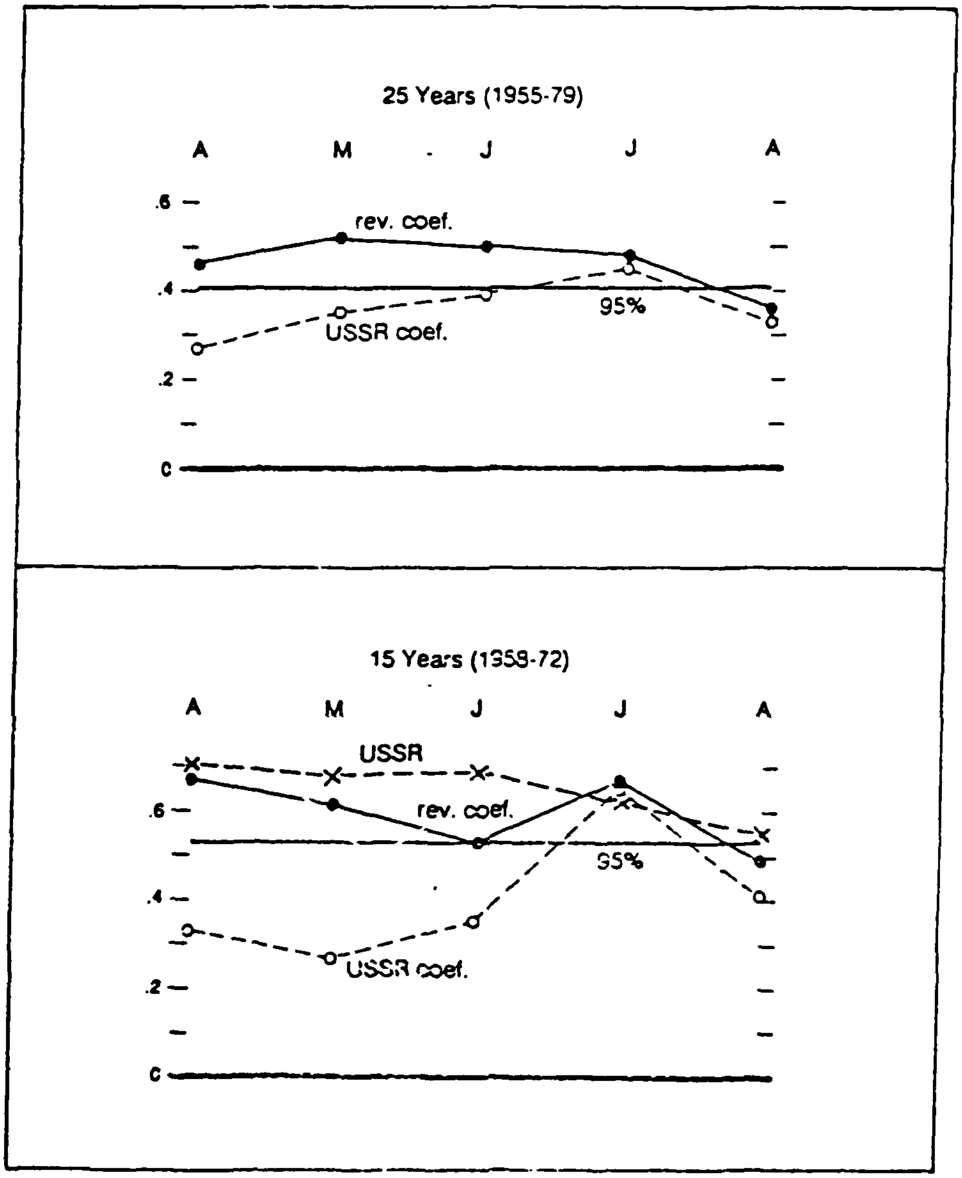

Figure 4.3 As for 4.2 except using values for the latitude band 73°–78° N.

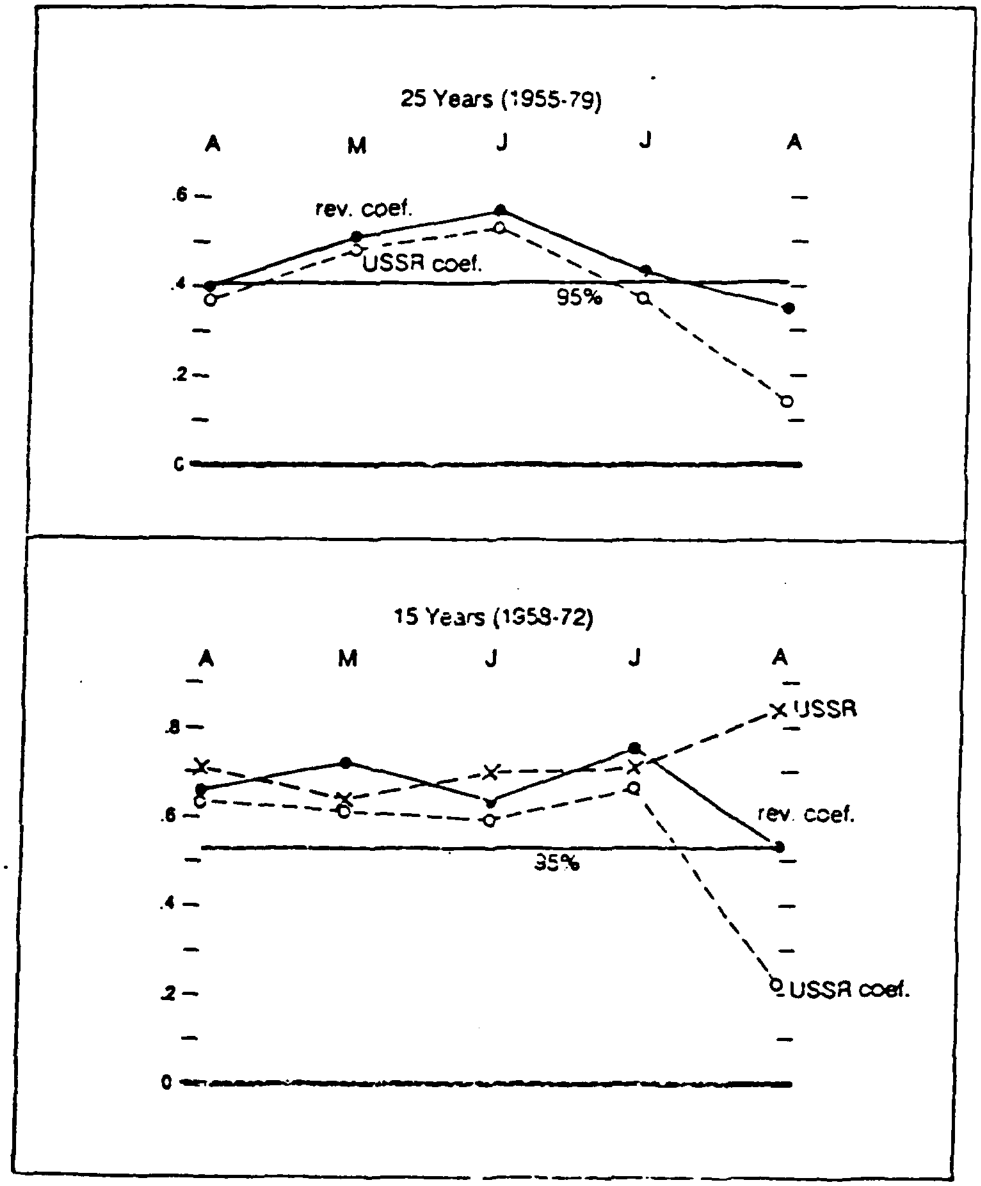

Figure 4.4 As for 4.2 except using values for the latitude band 68°-73° N.

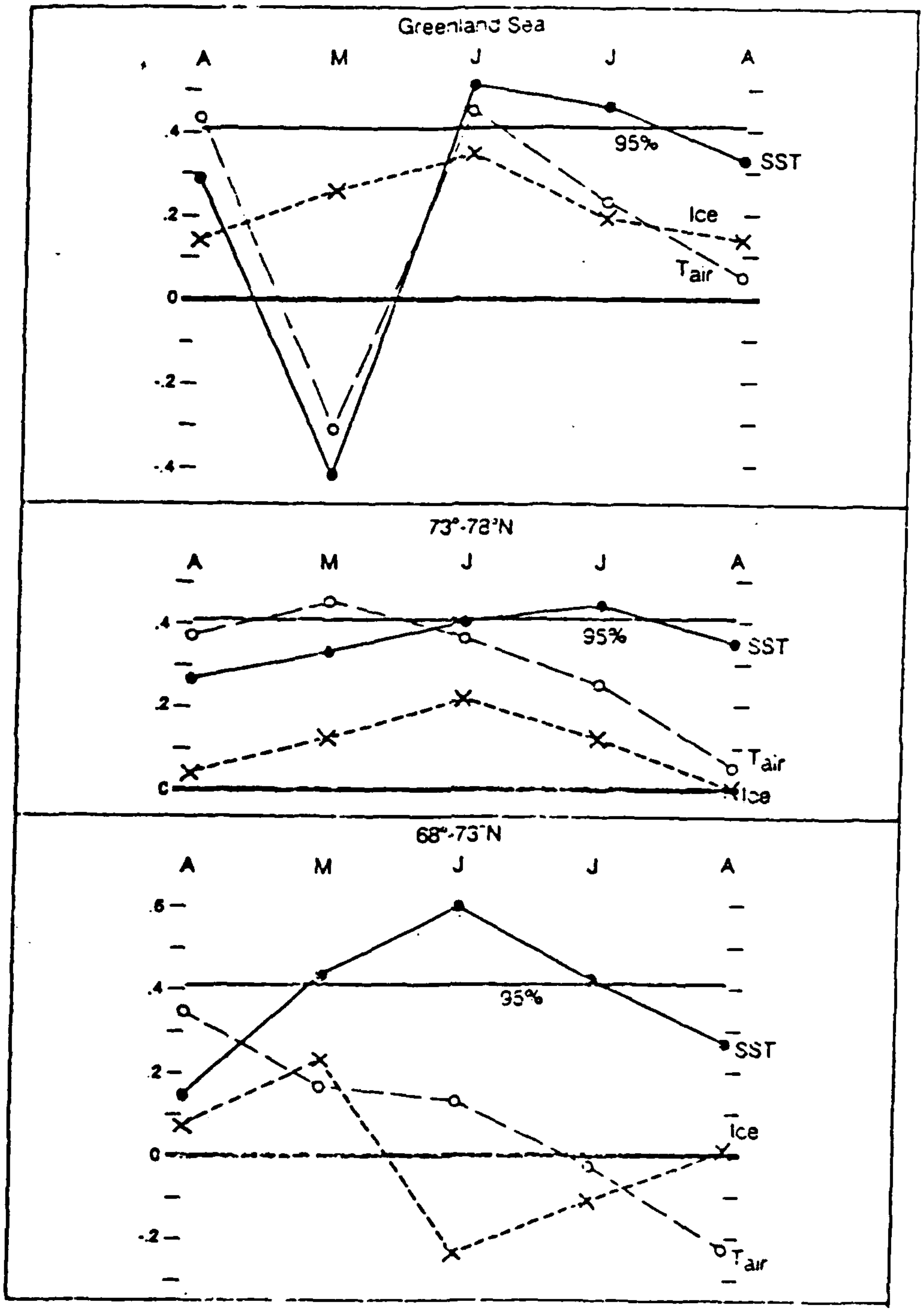

Figure 4.5 Correlations between ice cover and the three individual predictors (ice, surface air temperature, and SST) for the three regions. The 25-year (1955–1979) data set is used.

PART 2

<u>Evaluation of Smirnov's Alaskan Sector Forecast Model</u>

The regression equations developed by Smirnov (1979) were tested using U.S. data bases of Point Barrow temperature, pressure differences between Point Barrow and Alert, and ice flux through the Fram Strait. Comparisons were made between the published Soviet equations and equations derived from the U.S. data bases. Equations 2, 3, 5, and 7 of the translated equations required some modifications of either coefficient signs, decimal point placement, or to change "sum of" to "average of". Other minor differences were noticed between the two available translations of the Soviet article. The ability to closely duplicate some of the Soviet results, but not others, when using a particular predictor data base implies problems in interpolation by the author or in the original translation. The existence of translation errors and the requirement for subjective changes raises the point that all such evaluations and interpretations must be viewed with a critical eye.

The upper panel in Figure 1 shows the correlations of the Soviet regression equations using the U.S. data bases for the dependent years (closed circles) and independent years (open circles). The three sets of predictors, Barrow temperature (B_T), pressure difference between Barrow and Alert (P) and ice flux through the Fram Strait (F) are labelled across the top. The equation numbers, 1 through 18, are as in Smirnov (1979). The lead time of each of the 18 equations is labelled across the bottom of the Figure. The equations for each month of

verification are separated by vertical lines with the label of the month of interest near the top of the Figure. The equations using aspects of the Barrow temperatures as predictors behave in a reasonable manner when applied to the independent data, that is there are no significant changes in correlations between dependednt and independent years. The pressure differences also show fairly stable results. However, the independent cases of the equations using the Fram Strait ice flux as predictors (4, 9, 10, 11, 17) show a significant decrease in correlation with the Alaskan sector ice conditions. In a further investigation of these equations it was determined that the Arctic region of maximum correlation with the Fram Strait ice flux shifted from the Alaskan region to off northeast Siberia about the time of the change from dependent to independent years, around 1970. A further check of the mean surface pressure patterns before and after this time indicated a westward shift of the Arctic anticyclone center from the Alaskan sector toward the Siberian sector. This apparent circulation change and its relationship to Arctic ice condition patterns is addressed in more detail in Appendix C, part 2.

Smirnov's approach was next evaluated by deriving regression equation coefficients from the U.S. data bases for the same dependent years he had used and then tested on the independent years. Some results differed and can be explained by expected differences in data bases during the dependent years used to derive the regression equation coefficients. The results of the analyses of U.S. equations and data bases are shown for the dependent and independent periods in the lower panel of Figure 1.

To evaluate the equations using the Fram Strait ice flux an ice flux data base had to be generated as no data base of this parameter was known to exist. The procedures followed in development of this ice flux data base are described in Appendix C. The initial mean monthly values extracted from historical literature had assumed 10/10th ice coverage across the Fram Strait. Modern data, based largely on satellite data, indicated various seasonal reductions below 10/10th. Therefore the flux data base was modified to reflect this reduction and the results on the regression analysis is shown in the lower panel of Figure 1 by the added square markers under equations 4, 9, 10, 11, and 17. The coverage adjustment improved the correlation values in all the dependent cases and in four out of five for the independent cases. As with the Soviet equation evaluation, the independent ice flux equation results lost all meaningful skill for the Alaskan area ice conditions. However, correlations greater than .70 were found for the 120°E-140°E Arctic sector off Siberia.

The evaluation of Smirnov's approach indicates that the equations using Barrow temperature values contain some skill in predicting the late summer (Aug/Sept) Alaskan ice conditions. This was shown in both Smirnov's and the author's derivations of equations 7 and 8. The skill indicated in Smirnov's equation 16 was not reproduced by the authors form of equation 16. It is expected that this is due to a translation problem in light of the success in duplicating Smirnov's results with nearly all other equations using the Barrow temperature data.

The most interesting finding in this evaluation was the high correlation between Fram Strait ice flux and Arctic sector

ice conditions. Both this finding and the apparent Arctic circulation pattern shift are noteworthy and is thought to be new information to western scientists. There as yet has been no indication in the Soviet literature reviewed that they have detected the Arctic surface pressure pattern shift and its role in ice conditions. Additional research and evaluation of this finding should be made to achieve better understanding of it and its potential for use in extended range ice condition forecasting.

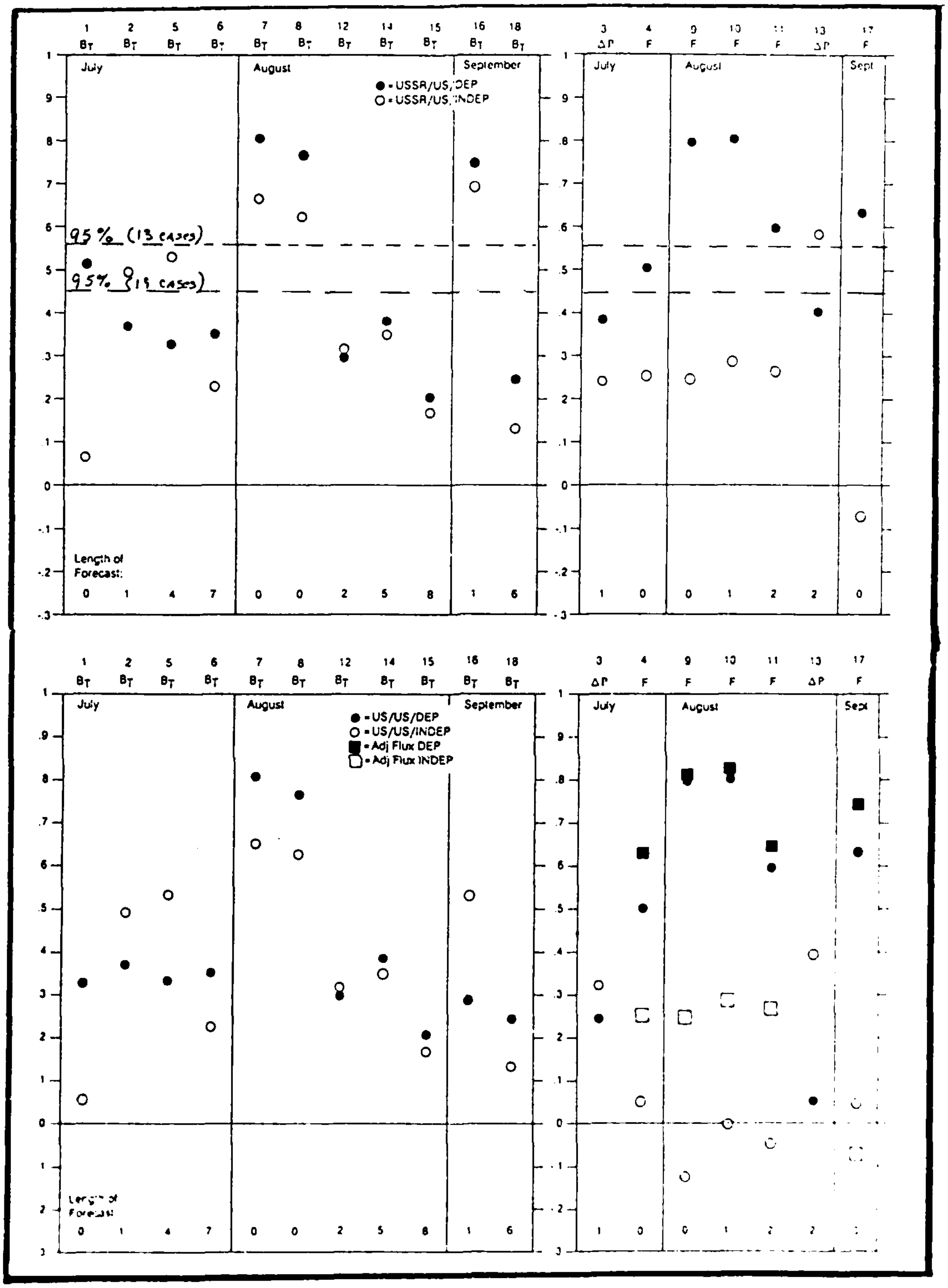

Figure 1. Correlations of Alaskan area ice conditions and Point Barrow temperatures (B_T), pressure differences between Point Barrow and Alert (P) and ice flux through the Fram Strait (F). Regression equations are based on Smirnov (1979) applied to U.S. data bases (upper panel) and on independent equations derived from the U.S. data bases (lower panel). The 95% confidence limits are shown for the 19 case dependent and 13 case

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[1] Problems of the Arctic and the Antarctic

APPENDIX C

Articles Published Under

ONR Contract N00014-87-C-0039

Sponsored by

Dr. Leonard Johnson, ONR
and
Dr. Elliot Weinberg, NCIST

Part 1

A Survey of Soviet Literature on Extended Range
Forecasting of Arctic Ice Conditions

by

Ronald E. Englebretson

In

Proceedings
of the
1987 U.S. Navy Symposium on Arctic/Cold Weather
Operational Support for Surface Ships
OP-03C2

Part 2

Fram Strait Ice Flux Calculations and
Associated Arctic Ice Conditions

by

Ronald E. Englebretson and John E. Walsh

In

Geojournal
mid-1988 Special Edition on the Arctic

Appendix C Part 1

A Survey of Soviet Literature on Extended Range Forecasting of Arctic Ice Conditions

by

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under

ONR Contract N00014-87-C-0039

Dr. Leonard Johnson ONR

Dr. Elliot Weinberg NCIST

To be published in the Proceedings

of the

1987 U.S. Navy Symposium

on

Arctic/Cold Weather Operational Support

for Surface Ships

A Survey of Soviet Literature on Extended Range Forecasting of Arctic Ice Conditions

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ABSTRACT

The Soviet coastline borders on 44% of the Arctic Ocean boundary. They have lived for years with or on, and now likely in, the Arctic Ocean. This is reflected in their stress of practical applications to operational problems in their research and development endeavors. A survey of their approach to Arctic forecasting and related environmental data collection is provided in this paper. The survey is based on a review of translated articles from the 1960's through the early 1980's. A significant shift in emphasis by the Soviets on the forcing of weather patterns and climate trends occurred during the 1970's. This shift marked a break from the classical Soviet hydrometeorological research on the cyclic nature of solar activity and earth/lunar orbital patterns and their relationship with atmospheric patterns, to studies of the physical interactions between the atmosphere/ocean/cryosphere. Throughout this evolution they have largely utilized empirical/statistical models for long range forecasting and analytical models for analyses and short range forecasting.

Their approach lends itself to locating their forecast capabilities at or near the operational site, which they tend to do, rather than at remote central sites, with large computer resources, as has been the U.S. approach.

A partial listing of what the Soviets are doing in Arctic environmental work and data collection and the type of systems they have developed is provided in a later section and further reflects their approach of "doing it" in the field. In the area of satellite data, they have had an operating side looking radar (SLR) since 1983 on the COSMOS satellites. While it does not have the sophistication, capabilities, or cost of the U.S. synthetic aperture radar (SAR), the SLR does provide important information on multi-year ice concentrations and other ice conditions. The Soviets combine SLR data with visual and infrared images to produce operational ice condition charts. The Soviets have at least four nuclear icebreakers, a number of ice reinforced supply vessels, several scientific research vessels, Arctic capabilities in both fixed and rotor craft, and two (sometimes three) year around manned drifting ice camps. The latest drifting station as of Dec 1986 (SP-28) is equipped with a ground satellite station, mini computer for data processing, satellite communications, and weather chart (facsimile) broadcasting systems. There is little doubt as to who has the homefield advantage relative to environmental observations and most likely forecasting in the Arctic.

1. Introduction

This paper is based on a survey of Soviet literature conducted under ONR contract N00014-87-C-0039 for Dr. Leonard Johnson, Office of Naval Research and Dr. Elliot Weinberg, Navy Center for International Science and Technology. The prime objectives were to review the translated Soviet unclassified literature on extended range forecasting in the Arctic, identify key Soviet personnel and approaches, select suitable Soviet models for evaluation, and comment on the Soviet capabilities.

Long-range forecasting in this study refers to forecasts for a month or longer. The ice conditions typically addressed by long-range forecasts include; general severity, time of opening/freeze-up, and relative extent of ice cover. It was found that the Soviets have pursued this problem more vigorously and continuously than the U.S. While the U.S. environmental community generally went off in search of bigger computers and better dynamic models during the last 25 years, the Soviets stressed analytical models and empirical physicostatistical models. The Soviet approach to some degree was mandated by limited computer power. However, it also lends itself to the somewhat limited area (non-hemispheric) that the Soviets were most concerned with during the early parts of this period. Now with the high interest (continuous on their part, new on ours) in the Arctic their by chance border location with 44% of the Arctic Ocean boundary and earlier special emphasis on the home sector of the Arctic are

likely to pay dividends. They have collected long period records of Arctic environmental parameters and have learned to apply many of them through analytical models and statistical analyses to real world in situ problems.

Being forced by year-in and year-out tasks of building, operating and resupplying Arctic coastal harbors and stations, as well as drifting ice camps, they have developed significant air and surface platform capabilities. They have designed both fixed and rotor wing craft for Arctic environment operations and their surface capabilities include nuclear ice breakers, a large number of ice reinforced supply vessels, and several research vessels. A number of environmental sensors and systems have been developed for use on the various platforms including: airborne facsimile sender, side looking radar, infrared radiometer, and laser altimeter for ice reconnaissance planes, aerial thermal sensors for ice thickness measurements, and shipboard hardware/software complex for satellite data processing.

Information Sources

The Soviet materials reviewed in this project came from the following translation services and original Soviet sources:

* Problems of the Arctic and the Antarctic (PAA). Quasi annual volume published by the Arctic and Antarctic Research Institute (AANII). Translated by Amerind Publishing Co., New Delhi for the Division of Polar Programs, National Science Foundation.

* U. S. Joint Publication Research Service (JPRS), a subordinate element of the Foreign Broadcast Information Service (FBIS). Soviet reports of interest: Earth Sciences, Space and Meteorology and Hydrology.
* Translated Soviet journals available in local libraries include: Meteorology and Hydrology, Oceanology, Atmospheric and Oceanic Physics, Doklady (Earth Science) and Trudy (Physical Science) of the U.S.S.R. Academy of Science.
* A variety of other government sources of unclassified translated material.

The initial literature review conducted during the first half of the project contained only a few references from the early 1980's, most of the references dated from the 1960's and 1970's. This provided an excellent review of the background on Soviet Arctic forecasting approaches, but not on their current work. During the later part of the project reference material through late 1986 was obtained. Most of the recent Soviet material was in the from of Soviet News Abstracts Publication (SNAP) and therefore are of a public relations format rather than scientific articles. The material reviewed did provide adequate intelligence to describe a major shift in the Soviet focus on extended range forecasting in the 1970's and indications of a dynamic move to satellite and computer technology in the mid-1980's following the launch of their COSMOS oceanography research satellite series.

2. FINDINGS

The Soviets have conducted a great deal of research related to Arctic extended range forecasting. Much of this research was initiated as a result of the Soviets' use of Arctic seaways for commerce and naval activities. Their studies differ in several ways from the Arctic studies conducted in the United States. First, their research programs have been relatively strong and continuous during the last half century and as a result the Soviets have more Arctic researchers than all the western countries combined. Secondly, the Soviets have approached various Arctic problems from a more practical applications and analytical viewpoint than U.S. scientists. The following sections on Long-Range weather forecasting, Long-Range sea ice forecasting, and Observation programs reflect the findings of the authors during the literature survey to date.

Long-range Arctic weather forecasting

Through much of the 1950's and 1960's, the cornerstone of Soviet long-range weather forecasting was the "macrocirculation" typing system. This typing system can be traced back to the previous generation of Soviet meteorologists (e.g., Vangengeim). The leading proponent at the Arctic and Antarctic Research Institute (AANII) during the 1960's and 1970's was A. A. Girs (1973 and 1981). While much of the developmental work on this system was done at the AANII, the system provided input to the Soviets' operational

forecasts for the entire hemisphere until at least the early 1970's (Livezey and Jamison, 1977). Multi-year changes in the frequency of these types were claimed to be attributable to cycles in solar (sunspot) activity and the solar-lunar tide (e.g., Karklin, 1975 and Dmitriev, 1975). Evidence of these cycles was also claimed to exist in sea ice variability, presumably through variations in the dynamic and thermodynamic forcing of the ice by the atmosphere. It should be noted that the solar-weather link was openly recognized as being quite subtle by some AANII scientists even in the early 1970's. Smirnov (1973), for example, notes the high-latitude SLP fields correlate highly with solar activity only when the SLP data are filtered by computing the differences running 7-year and 11-year means. Smirnov concludes that the "role of solar activity ... is not decisive even in the region of the most pronounced effect on the Northern Hemisphere troposphere."

In recent years both internal and external assessments have placed Soviet capabilities in long-range weather forecasting into a more realistic perspective than implied by Soviet papers of the 1960's and 1970's. Livezey and Jamison (1977), for example, show that the skill of Soviet long range weather forecasts through the early 1970's was no better than control forecasts such as persistence -- although the Soviets' forecasts did display more skill for the Arctic than for other regions of the USSR. Volkov (1973) notes that the accuracy of long range forecasts even for the Arctic is not high: "...the frequency of correctly forecast signs of anomalies of Arctic temperature and pressure does not exceed 60-65%."

Recent Soviet reviews of the "state of the art" of weather forecasting in the USSR (Aristov and Ped, 1979 and Petrosyants, 1980) indicate that present methodologies are quite similar to those in the U.S. Short-range forecasts are based largely on LFM-type models and MOS procedures, although computer limitations are likely responsible for the use of only 4 layers in the model and for the frequent mention of model running time. Long-range forecasting tools listed by Aristov and Ped include the statistics of persistence and extrapolation, which are heavily used in the U.S. by NOAA/NMC's Long-Range Prediction Group. The weight given by the Soviets to North Atlantic SST, as well as to snow cover and soil moisture, appears to be greater than that at NMC. Marchuk's method of diagnosing 30-day temperature anomalies in terms of adiabatic and non-adiabatic components seems to be the Soviets' most novel technique, and perhaps merits investigation by U.S. forecasters. Petrosyants indicates that the Soviets attempt forecasts up to one year in advance, but no procedural details are given.

Long-range sea ice forecasting

Soviet efforts in long-range forecasting of sea ice will be distinguished here according to the numerical modeling and the empirical (statistical) approaches. While the Soviets have published considerably more literature on long-range ice forecasting by both approaches than have western scientists, the literature contains little specific information on the operational utilization of these forecasts. In the case of

the North Atlantic forecasts prepared by the Murmansk branch of the AANII, information on operational utilization may be classified. In the case of the western portion of the Northern Sea Route, where the Soviets claim to have begun year-round navigation in 1980 (Tolstikov, 1982), improved ice reconnaissance seems to be regarded as the most essential factor (TASS, 1985). However, Volkov (1973,) claims that Soviet economists' estimates indicate a gain of 360 navigation days during the 1960's as a result of planning decisions based on ice forecasts. A recent comment by Timokhov and Mustafin (1986) is relevant in this regard: "... the growth of the transport icebreaker fleet is outstripping development of equipment for its hydrometeorological support." It is unclear whether this statement refers to equipment for observing the ice or to equipment for transmitting information between forecast centers and the field.

The Soviet claim of high levels of skill for their models is often questioned by Western scientists. The Soviet verification tolerance answers part of this question. They establish their tolerance as fractions of the forecast parameter variance, typical tolerances are .67 sigma (standard deviation) for a month forecast and 1.0 for six month forecasts.

Numerical modeling

There is no indication that the Soviets currently employ a large-scale (Arctic Basin) numerical model for real-time ice prediction in the manner in which Fleet Numerical Oceanographic

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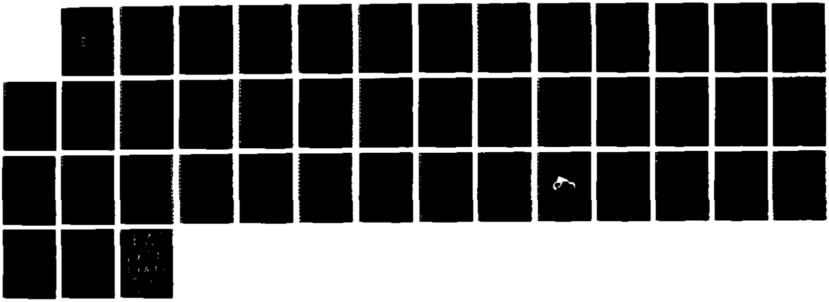

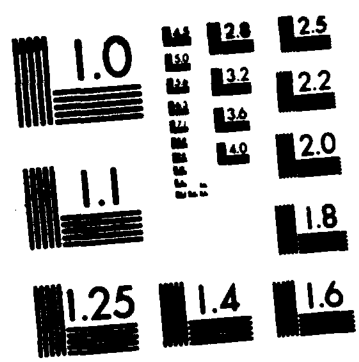

MICROCOPY RESOLUTION TEST CHART
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Center (FNOC) utilizes the Hibler/Prellor model. However, as indicated by the following review of focused modeling efforts, and in view of the Soviets' oceanic database, the gap in basin-scale simulation capabilities may be closing.

Two modeling topics on which the efforts and progress made by the Soviets exceed those of western modelers are (1) the simulation (prediction) of the autumn freeze-up, and (2) the parameterization of the summer melt. The freeze-up simulations have generally utilized variants of Doronin's (1960) also, Doronin and Sychev (1974) ice-ocean model containing a multi-level variable-depth mixed layer; salinity effects are included but ocean currents are "constant". Moskal' (1977), and Appel' and Gudkovich (1977) have applied this model to the Barents and East Siberian/Chukchi Seas, respectively. Smetannikova and Teitel'baum (1974) show a network of grid points in the Soviet Arctic for which this model is evidently used to produce operational forecasts of freeze-up dates. The model is, however, temperature-driven. Appel' and Gudkovich (1977) present a formulation of summer melt (albedo parameterization, lateral vs. bottom melt) that is considerably more sophisticated than the melt formulations used in the Hibler model and in GCM treatments of sea ice. In general, the Soviets seem to lead western researchers in formulating the albedo of sea ice, especially during the melt stages (e.g., Appel' and Gudkovich, 1977 and Nikolaeva and Sesterikov, 1976

Ice model simulations of a large segment of the Soviet Arctic (Kara, East Siberian, Chukchi Seas) have been reported

by Appel' and Gudkovich (1977). The model contains temperature-dependent ice growth rates, constant ocean currents, and a four-force momentum equation with a viscosity term for ice interaction. The latter is said to reduce the computing requirements considerably, thus giving an "indisputable advantage" to the model. This model was run with a two-day timestep for 27 different years (through 1972) for the September-May period, and the output was used to initialize simulations for the subsequent summer periods. Although they do not provide substantive verification statistics, the authors cite the need for better ocean current data and for the improvement of a number of "ad hoc" parameterizations. The need for improved current measurements north of Alaska and Siberia is also mentioned by Gudkovich and Teitel'baum (1977).

Appel' and Gudkovich (1984) have also performed a diagnostic model analysis of the possible changes in the Kara Sea salinity distribution that may arise from river discharge anomalies. These two scientists appear to be at the forefront of Soviet ice modeling efforts directed towards practical applications. Their work, together with the ocean modeling of Ponomarev and colleagues, may have put the Soviets on the brink of useful exploitation of numerical models for operational long-range ice forecasting.

Empirical strategies

While the Soviets appear to have lagged the West in the operational use of large-scale ice models, they have lead the

West in research on empirical forecasting strategies -- certainly in terms of the volume of published results and apparently in terms of the usefulness of these results. Empirical input has been used extensively in the preparation of seasonal forecast for the Gulf of Anadyr, the Chukchi, East Siberian, Laptev, Kara, Barents and Greenland Seas, and the Labrador Sea/Davis Strait. Long-range forecasts for the latter three regions were begun in 1971, while the forecasts for the Soviet Seas have been prepared since the mid-1940's (Kirillov, 1977).

The empirical procedures used by the Soviets have been developed from a sea ice data base containing two components. The first is the data set on sea ice in the Soviet Arctic, for which the relatively complete data coverage extends back to 1936 (Zakharov and Strokina, 1978). This data set has not been made available to western researchers. The second component is the data for non-Soviet seas, for which the Soviets have utilized widely available chart series such as the Danish ice yearbooks and the British ice charts for the North Atlantic; Canadian and U.S. charts for the North American Arctic; and, in recent years, imagery from U.S. and other satellites (Kirillov and Khromtsova, 1972). Thus the ice data that is available to the Soviets for statistical analyses pertaining to foreign waters is the same -- sometimes fragmentary -- data available to western researchers. The Soviets do seem to have exercised care in extracting indices of ice coverage from the non-Soviet data (e.g., Kirillov and Khromtsova's tabulation of Greenland sea ice coverage).

Especially in the last ten years, the published literature contains less detail on Soviet forecasts for their own waters than for non-Soviet waters. Volkov and Zakharov (1977) present a climate-flavored analysis of ice variability in the Soviet Arctic for the period 1945-1975. Yanes (1975) claims that the inflow of water through the Faero-Shetland region correlates "closely" ($r = -0.637$) with ice cover three years later in the northwestern Kara Sea. In a corresponding study of the Pacific sector, Arikainen (1976) reports that the autumn salinity measured at 5-6 Soviet stations correlates at 0.5-0.6 with the area of the Chukchi flaw lead the following June.

While not presenting details of the forecasting techniques for the Soviet Arctic, a survey paper by Volkov (1973) describe the major inputs as correlation statistics such as those above, thermodynamic model calculations of the freeze-up dates, and systematic ice reconnaissance to delineate the boundary between first-year and multi-year ice.

The published procedures for ice forecasts for the non-Soviet Arctic are, almost without exception, empirical. Kirillov (1977) notes that the accuracy of these procedures has been greater for the Atlantic seas than for the Pacific sector. (Results of ice forecasting studies by western scientists have not shown a similar regional dependence). Work by Lebedev and Uralov (1977) presents regression equations for Greenland Sea ice cover in terms of year-to-year persistence, October-February air temperatures from surrounding stations, and October-February sea surface

temperatures (SST's) at two North Atlantic weather ships. Explained fractions of variance are generally 30-60% at lead times of 3-6 months. (The physical mechanism by which SST anomalies influence the ice is claimed to be through their influence on the atmospheric circulation.

Predictability studies for the Danish Strait and Labrador Sea regions have been done primarily by scientists at the AANII's Murmansk branch. Nikol'skaya, Senyukov and Kogan (1977) use a 16-year data base to derive predictive regressions based on SST data from a set of nine North Atlantic weather ships. Correlations at lead times of one-two seasons are 0.4-0.5, although correlations involving more southerly SST's at one-year lead times are as large as -0.68. Fall-winter air temperatures over land are claimed to correlate at -0.73 with springtime ice in the Danish Strait. Kogan et al. (1977) use similar regression parameters for predicting spring-summer ice cover in the Danish Strait at 2-6 month lead times. Kogan and Orlov (1981) later include the intensity of the Icelandic low as a predictor, and use as predictors the <u>residuals</u> of autoregression model forecasts of ice cover. (This strategy of using atmospheric and oceanic predictors to improve upon "persistence" is often included in Soviet empirical procedures, and may merit further quantitative evaluation by U.S. forecasters).

For the Labrador Sea region, Orlov (1977) uses autocorrelation statistics to argue that the scales of the fluctuations are 200-250 miles and 30-50 days, and that the ice anomalies are carried along by the Labrador Current at 5-6

miles per day. Kogan and Orlov (1981) describe regression equations based on water and air temperatures at five North Atlantic weather ships, air temperatures at three coastal stations, and pressures from the Labrador Sea; "81% skill" is claimed for the forecasts made in September-October, i.e., at 4- to 5-month lead times. Kogan and Orlov also mention a new "dynamical-statistical" method of a Soviet scientist named Alekhin, and claim that grid-point forecasts made by this method are 80-90% reliable.

For the Baffin Bay and Alaskan regions, the most substantive empirical work by the Soviets appears to be that of Smirnov (1979). Various regression equations for the May-September ice cover in both regions are presented by Smirnov in terms of antecedent air temperatures (Barrow), pressure differences along several transects, and ice transport into the Greenland Sea. The equations can be used as early as January. However, the developmental data base is only 14-16 years, implying that considerably more data now exists than was used by Smirnov. Smirnov (1980) also claims to have detected an "opposition" of summer ice severity in the Baffin Bay and Alaskan areas.

Nearly all the published Soviet work on empirical sea ice forecasting through the early 1980's seems to have been done in a non-automated mode, i.e., without exploiting computer capabilities. Gudkovich (1981) comments that the Soviets plan "... in the very near future ... a transfer to the computer of very laborious searches for optimal predictors and construction of prognostic equations." Thus it is quite

possible that the empirical prediction techniques described here may by now have been superseded by more sophisticated procedures.

Analytical Models

The following comments on specific analytical models were provided by James Lewis of SAIC who has been conducting studies on ice kinematics under ONR contract N00014-87-C-0173 and also reviewed a number of pertinent Soviet references.

"Unsteady Wind Drift of Sea Ice" (Doronin and Shirokov, 1974)

This paper works with an analytical solution to the free drift equations for ice. A simple solution for unsteady drift was obtained by using the forces of the coefficients of turbulence. These solutions give two interesting findings. First, in regions with a greater percent of open water, the ocean current has a larger influence on the ice drift than other factors. Second, smaller floes accelerate faster than larger floes. The authors state that this latter factor is a result of friction on the sides of the floe, and is not a mass effect. They indicate that the total water resistance per surface area is greater for smaller floes than larger floes, and this allows for increased acceleration and deceleration. The concept is difficult to grasp.

"Pressure Distribution in Consolidated Ice" (D.Y. Kheysin and and V. O. Ivchenko, 1975)

This paper presents some results of a study of consolidated ice in a visco-elastic layer. The internal stresses of ice are written as gradients of the velocity. The authors split the linearized equations of motion into a divergent component and a non-divergent (shearing) component. These expressions allow one to take initial conditions and known drift velocities and compute the field of internal stresses.

Force balances equations are developed for the ice, wind, and water, all of which have expressions for motion, continuity, and energy. A model grid is set up with a 111 km spacing. Starting with zero ice velocities, the model gave stationary drift in 2.5 to 3 hours. The results showed strong ice compression in regions of anticyclones and rare-faction in regions of cyclones. These results have been shown by other studies to be the case when internal ice stresses are small (i.e., during summertime conditions).

"Ice Movement in the Arctic Basin and External Factors" (A.P. Legen'kov, 1978)

The author formulates ice motion as a function of local wind forcing as well as forcing by wind in adjoining areas. Seeing that pressure is transmitted in consolidated ice at a rate of about 10 m/s, he concludes that often pressure can propagate ahead of the wind. For smaller time intervals, ice motion is shown to be poorly correlated in space. The author

attributed this to random motion. With longer time intervals the general correlation of motion in space increases, a reflection of less influence of random motion. His conclusion was that the dependence of ice motion on external factors increased with time. Thus, randomness of the movement of floes with respect to each other decreases with increasing ice concentration and with increasing time scales of averaging.

<u>"Relationship Between Mean Stresses and Local Values of Internal Forces in a Drifting Ice Cover"</u> (D.Y. Kheysin, 1978)

The author developed an ingenious analytical model by which he could integrate the internal forces over a region to obtain the mean stresses. He stated that, over a grid space of a model, stresses were normally 10^4-10^5 dynes/cm^2, perhaps as high as 10^7 dynes/cm^2. However, ships have measured directly up to 10^9 dynes/cm^2 on their hulls. The author attributes this discrepancy to the fact that "effective" stresses (averaged over sizable areas) are calculated by models. Thus, maximum stresses are averaged out.

An expression is developed for small scale stresses. He then averaged this expression over a larger area. As a result, he established the mathematical framework by which one can go from the stress of a numerical realization of a large scale drift model to the computation of compression forces of ice acting hulls of ships in the ice.

<u>Observational programs</u>

A key component of the Soviet system of ice forecasting is their program of systematic surveys and other observations of

sea ice, ocean and atmospheric variability in the Arctic. The annual springtime oceanographic surveys have provided the Soviets with a data base that can provide considerable advantage in diagnostic and modeling studies of large-scale ice-ocean coupling. These surveys are said to cover most of the Arctic Basin at grid intervals of 125-300 km (Belyakov et al., 1984).

Weather and ocean information is also transmitted 12 times per day from the Soviet SP drifting stations, of which there has been generally two to three in operation. These are supplemented by automatic stations, patrol ships and jumping teams (Tolstitov, 1982), presumably on a less regular basis. Terziev (1977) claims that the three "expedition vessels" of the AANII's Murmansk branch survey 35,000-40,000 miles each year in the northern seas and the North Atlantic, servicing more than 1500 buoys and irregular stations.

Ice reconnaissance has been described as an "indispensable part" of operational navigation of the Northern Sea Route. The January aircraft surveys of over 10,000 km, Murmansk to Uelen, are said to be used for both short-term and long-term forecasts. An "airborne facsimile sender" is carried on these surveys; on-board data storage devices are also used (Murlin, 1985). Aircraft include two IL-14's and, in the near future, an AN-74 aircraft capable of landing on ice (TASS, 1985).

Key aircraft instrumentation includes the "Toros" side-looking radar, radar ice thickness gauges, IR radiometers, laser altimeters, and aerial cameras. A recently-developed "Led-2" (radar) instrument is said to measure ice thickness

from aircraft, and to identify cracks and channels even if those features are obscured by new ice or snow. The value of these instruments to the Soviets may be indicated by the fact that the 1984 USSR State Prize was given to the five scientists who developed the radar instrumentation for the ice thickness measurements (Murlin, 1985).

Following the launch of the initial COSMOS satellite of their oceanographic scientific series, the Soviet researchers commenced an active program on developing theory, methods and means of remote probing of the ocean and cryosphere. The 25 October 1985 JPRS-USP-85-008-L (Space), articles on COSMOS-1500 Oceanographic Satellite contain an overview article on the COSMOS program and some twenty articles on applications. The program overview provides a list of mission goals of which the first is, "to develop and improve methods and means of remote probing of ice fields." The first four articles following the program description were on sea ice. A total of six articles related specifically to interpretation of ice conditions and four others included ice related information, while the remaining articles addressed patterns of near-surface winds, sea surface temperature, and instrumentation discussions. The growing importance to the Soviets of data from the COSMOS sensors in ice studies, as well as studies of the ice itself, are indicated by this emphasis on sea ice articles.

The COSMOS series launch dates and key sensors are:

COSMOS #	Launch Date	Sensors
1076	02/79	IR/MICROWAVE
1151	12/80	IR/MICROWAVE
1500	09/83	SLR/IR/MICROWAVE
1602	09/84	SLR/IR/MICROWAVE
1766	07/86	SLR/IR/MICROWAVE

The COSMOS program article comments on the Side Looking Radar (SLR) as new research equipment on the COSMOS 1500 satellite. The additional articles on ice all stressed features and interpretation of the SLR data. The SLR is reported to provide excellent information on coverage of multi-year ice, areas of channels, leads or polynyas, ice drift vectors, and compression trends. Acknowledged problems include % of hummocking and identifying new ice or first year ice from smooth sea surfaces. A special application has been the production of ice coverage charts by combining the projection of SLR and visual/IR images.

In addition to their COSMOS series satellite, the Soviets operate a set of photographic reconnaissance satellites for Arctic ice monitoring. These satellites have an inclination of 82 degrees (measured counterclockwise from the equatorial plane) and are at an altitude of 150 miles. They are especially useful in monitoring spring breakup and fall freezes (Kramer, 1987).

3. ASSESSMENT OF SOVIET RESEARCH

The Soviets appear to lead the west in total research and development efforts in Arctic related matters. They currently have a number of application advantages including: available data bases from their sector of the Arctic, background studies (airborne plus ground truth data) using SLR and IR sensors, satellite SLR data, development of analytical models useful for in situ analysis, empirical/statistical long-range forecast models, a significant edge in the number of personnel with Arctic operational experience and a large number of surface and air platforms designed for polar operations.

The Soviets have developed a number of modeling techniques by which observations can be used to calculate critical sea ice parameters. - The parameters include:

a. mean ice thickness,

b. the field of internal ice stresses, and

c. local scale internal ice forces.

These techniques appear to be a direct outgrowth of the Soviets' use of analytical solutions to the governing equations as opposed to the application of numerical models.

Through the 1970's the Soviets lack of sophisticated computer technology restricted their development of complex models. This problem appears to be largely eliminated at this time. Up to the end time of the articles reviewed in this project there was a continued emphasis on statistical methods for long-range forecasting efforts, this is expected to continue. The Soviets have taken a regional approach to both

short and long term forecasting. This approach maximizes the usefulness of local data and allows for tuning models to regional forcing and responses. Global models do not have this option and are generally tuned to provide either the best hemispheric wide skill or skill for some specific region at the cost of others.

A final statement on Soviet environmental related efforts is that the closer one gets to them and the more localized and short-time scale the point of concern is, the better the Soviet performance is likely to be. This is basically a universal finding when going into the other sides arena to play their game.

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Appendix C Part 2

Fram Strait Ice Flux Calculations and Associated Arctic Ice Conditions

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Submitted for publication in the special 1988
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INTRODUCTION

Because the Fram Strait is the primary outflow region for sea ice from the central Arctic (Tucker, et al, 1987), the export of ice through Fram Strait can be expected to play a major role in the mass balance of the Arctic ice pack. The areal outflow of Arctic ice through Fram Strait is highly variable over both seasonal and interannual timescales (Vinje and Finnekasa, 1986; Untersteiner, 1987). The magnitude of the areal flux of ice is controlled by atmospheric circulation, ocean currents, and the supply of ice at and upstream of Fram Strait.

The Transpolar Drift Stream represents the primary supply route for the ice entering the Fram Strait outflow region (Fig. 1). The key atmospheric features affecting the Transpolar Drift Stream are an anticyclonic gyre, which in the long-term mean is centered north of Alaska near 75°N, 155°W, and a trough of low pressure extending northeastward into the Barents Sea from the Iceland region. The source region for the ice in the Transpolar Drift Stream is determined largely by the anticyclonic gyre (Fig. 1), which in turn responds to atmospheric forcing through the surface wind stress and the surface energy balance.

The physics of the ice/water exchanges through Fram Strait have recently been addressed by Untersteiner (1987), while the variability of the ice drift both upstream and downstream of the Fram Strait outflow region has been examined by Vinje and Finnekasa (1986) using available buoy data, primarily from 1976-1984. Both authors present evidence of large year-to-year variations in the outflow. The present work is intended to (1) extend the analysis of Fram Strait outflow variations to the longer timescales ($\leq$ 30 years) associated with climatic trends or changes, and (2) determine whether

variations in the Fram Strait have larger-scale implications for ice variations in other regions of the Arctic. Any evidence of longer-term and larger-scale changes of the kind addressed here can provide a background for the assessment of shorter-term changes. Such evidence will also provide a perspective for future changes that may result from increasing concentrations of atmospheric carbon dioxide. The scales of the variations examined here are likely to require consideration of all three high-latitude climatic components: atmosphere, ice, and ocean. The emphasis in this work will be on the first two components.

ESTIMATES OF FRAM STRAIT ICE OUTFLOW

Long-term measurements of the ice flux through Fram Strait, as well as published information on long-term changes in the general physical properties (thickness, age, etc.) of sea ice in the Arctic Ocean are lacking (Weeks, 1986; Wadhams, 1981). The available estimates of the ice export are generally based on the period of enhanced buoy coverage since 1976 or on the material in earlier Soviet publications. Soviet scientists have used the Fram Strait ice outflow as a predictor in the statistical forecasting of Alaskan regional ice conditions. Smirnov (1979), for example, presents several regression equations in which summer ice coverage in the Alaskan area is inversely proportional to the ice flux into the Greenland Sea during antecedent periods containing the previous winter and spring (Table 1). An effort by the present authors to evaluate USSR statistical forecast methods indicated the need for an extended data base of monthly outflow and motivated the work described in this paper.

Table 1. Summary of Fram Strait ice flux predictor and Alaskan ice area predictands used in linear regression equations of Smirnov (1979). The term "admissible error" is not precisely defined by Smirnov, but is presumed to represent a standard error of the estimated ice-covered percentage of the Alaskan waters.

Smirnov (1979) equation #	ice predictand	flux predictor	ΔS (%), ("admissible error")
4	July	June-August	14
9	August	October-September	12
10	August	June-August	14
11	August	October-June	14
17	September	October-September	12

The total ice flux is comprised of a wind-driven and a current-driven component. Vowinckel (1964) provided estimates of monthly mean exports by wind and by ocean current under various prescribed annual East Greenland Current speeds at 80°N. In the absence of data on its seasonal cycle, the East Greenland Current speed was assumed by Vowinckel to be seasonally invariant. Table 2a contains Vowinckel's mean monthly wind- and current-driven components of the ice flux.

While the mean values are of interest in themselves, they do not provide the interannual variation required for statistical analysis or for the testing of published predictive equations such as those of the Soviets (Smirnov, 1979). In order to provide an historical data base depicting interannual variations over periods preceding the buoy era, a proxy relationship was developed. It was assumed that the north-south geostrophic wind is proportional to the sea level pressure gradient across Fram Strait. The pressures required for the computations were obtained from the National Center for Atmospheric Research in the form of monthly 5° x 5° latitude-longitude grids, and the endpoints of the transect used for computing the pressure difference across Fram Strait were 80°N, 20°W and 80°N, 10°E.

The correlation between the long-term mean monthly pressure differences along this transect and Vowinckel's mean monthly wind-induced ice flux was found to be 0.86. On the basis of this correlation, the ratio between the long-term monthly mean wind-driven ice flux of Vowinckel and the monthly mean pressure differences was used to estimate wind-driven ice exports for each month and year. Specifically Vowinckel's ratio of 6600 km^2:1 mb was applied to the individual monthly pressure differences to develop a proxy time series of the wind-driven ice outflow for each month of the 34-year

Table 2. Monthly and annual mean ice transport (km^2) through the Fram Strait: (a) values from Vowinckel (1964), (b) values based on proxy wind-driven fluxes (see text) and Vowinckel's current-driven fluxes, and (c) total flux values as in (b) but adjusted for monthly ice coverage across Fram Strait.

(a) Vowinckel				(b) Proxy wind				(c) Adjusted for ice coverage	
Month	Wind	Current	Total	Month	Wind	Current	Total	Month	Flux
1	26570	58860	85430	1	24860	58860	83720	1	71380
2	28930	58860	87790	2	25170	58860	84030	2	78820
3	30500	58860	89360	3	18560	58860	77420	3	65930
4	29230	58860	88090	4	23950	58860	82810	4	70760
5	15450	58860	74310	5	9610	58860	68470	5	54600
6	9280	52320	61600	6	6810	52320	59130	6	43050
7	1550	52320	53870	7	4020	52320	56340	7	38360
8	4010	45780	49790	8	1880	45780	47660	8	28030
9	14400	45780	60180	9	19630	45780	65410	9	44260
10	22440	52320	74760	10	15560	52320	67880	10	52160
11	27190	58860	86050	11	30310	58860	89170	11	70860
12	27810	58860	86670	12	29140	58860	88000	12	76630
Annual	237360	660540	897900	Annual	237360	660540	870040	Annual	694840

period, 1951-1984. The 34-year mean monthly wind-driven fluxes were added to Vowinckel's mean monthly current-driven flux values to produce the mean monthly and annual flux values as shown in Table 2b. The derived annual wind-driven fluxes for individual years are shown in Fig. 2. It should be noted that the current-driven components do not vary interannually and thus have no effect on the correlations with ice coverage described in the following section.

The 80°N transect used here does not necessarily provide the optimum measure of the atmospheric forcing relevant to Fram Strait ice outflow. Vinje and Finnekasa (1986), for example, show that about 50% of the East Greenland ice drift speed (lagged by one week) can be explained by the air pressure difference between 81°N, 15°W and 73°N, 5°E. For the longer-term variations examined here, it was felt that the most objective choice of a pressure parameter was simply the difference between the 5° x 5° grid points closest to the boundaries of the Fram Strait.

Although Vowinckel's (1964) computations are based on the assumption of 10/10 ice coverage, the ice concentration can be expected to affect the individual monthly flux values in the sense that the export will increase with the amount of ice available for export. The weekly analyses of ice coverage produced since 1972 by the U.S. Naval Polar Oceanography Center, Suitland, indeed show that the ice concentration across the Fram Strait is often considerably less than 10/10. The wind- and the current-driven values computed here were therefore adjusted according to the departure from the 1972-84 monthly mean ice coverage along the east-west transect shown in Fig. 3. When the "adjusted" fluxes (Table 2c) were used to test the Soviets' as

well as our own regression equations for summer ice coverage, the correlations between the Fram Strait ice outflow and Alaskan area ice coverage were larger than those obtained without the concentration-adjustment.

It is apparent from Table 2 that concentration-adjusted computations produce annual mean fluxes that are considerably smaller (0.69×10^6 km^2) than Vowinckel's (1964) value of 0.90×10^6 km^2, Volkov and Gudkovic's (1967) 0.90×10^6 km^2, Koerner's (1973) 1.51×10^6 km^2, and Vinje's (1982) 1.08×10^6 km^2. Only Zakharov's (1976) value of 0.65×10^6 km^2 is close to the annual mean obtained here. The apparent discrepancy arises largely because the transect used to compute the concentrations is somewhat south of the Fram Strait. Ice concentrations in the eastern portion of Fram Strait decrease repidly south of 81°N, and the concentration-adjusted fluxes in Table 2c are most valid for several hundred kilometers south of 81°N. Alternatively, the fluxes in Table 2b may be regarded as more appropriate values for ice entering the strait at ~81°N, where the ice concentrations average much closer to 10/10 in the database used here.

COMPARISON WITH ICE COVERAGE

Monthly ice coverage in the northern Alaskan waters (Fig. 1) was correlated with the computed Fram Strait ice outflow. The ice coverage data for the years 1953-1971 was obtained from the dataset of Walsh and Johnson (1979) and for the years 1972-1984 from the digital database of the U.S. Navy/NOAA Joint Ice Center. The Alaskan area as defined here is the region bounded by 70°N, 75°N, 130°W, and 170°W (see Fig. 3). The USSR equations, listed in Table 1, were developed by Smirnov (1979) using data from the period beginning in 1955 and ending in 1969-70. The Soviets' results and

our own correlations are in general agreement for the 1955-71 period when the correlations are quite high. However, the Soviet equations lose much of their apparent skill when applied to the independent years, 1972-84 (Fig. 4).

It was noted earlier that the source of the ice coverage data changed in 1972 when the digitized analyses of the Navy/NOAA Joint Ice Center became the sole input to the sea ice dataset. The post-1972 grids are characterized by more detail in most Arctic seas. This additional detail, which shows periods of considerably less than 10/10 coverage across Fram Strait, leads to a general decrease in the annual concentration-adjusted ice flux values. However, the correlations for the post-1972 period in Fig. 4 were based on departures from the 1972-84 mean. Since these departures showed no general trend after 1972, we conclude that the Alaskan ice fluctuations within the period were not as closely related to the Fram Strait outflow as during the earlier period.

Rather than the change of the ice data source, a potentially more interesting change appears to underlie the correlation statistics described above. Figure 5 shows the correlations between (1) June-October ice coverage in all 20° sectors of the Arctic and (2) the average pressure differences across Fram Strait during antecedent and concurrent periods. Separate plots are presented for the periods prior to and beginning with 1972. While the correlations for the Alaskan sector decrease substantially in the later period, the correlations in the Siberian sector (120°E-140°E) are similar to those obtained for the Alaskan region during the earlier period. This change suggests that the source region for the Transpolar Drift Stream may have shifted westward during the study period. Such a shift in the axis of

the Transpolar Drift Stream would imply a change in the large-scale atmospheric forcing pattern. Figure 6 shows that the center of the Arctic anticyclone was indeed farther west during the March-June period in 1972-84 than in 1953-71. The shift of the atmospheric gyre's center from 75°N, 120°W (Fig. 6a) to 77°N, 155°W (Fig. 6b) is such that less association between northern Alaskan ice and the transpolar drift is implied for the later period. The time series in Fig. 7 show that the correspondence between the two quantities indeed decreased noticeably in the early 1970's. The geostrophic wind pattern in Fig. 6b implies that the Siberian coastal waters in the 80°E-140°E sector were the primary source regions during the later years. It should also be noted that the Barents Sea cyclone was less prominent during the later period. Whether or not this change contributed to the geographical shift of the Arctic anticyclone is not known, but the changes do point to a need for a more quantitative understanding of the large-scale changes of the high latitude atmospheric circulation.

Figure 5 also shows that summer ice coverage in the Greenland Sea sector is positively correlated with the Fram Strait outflow, although the region of positive correlations is much broader longitudinally during the later period. More specifically, the outflow during March-July correlates at better than +0.5 with the June-October ice coverage during 1972-84. The plot for the more recent years (Fig. 5) also indicates that correlations with regional ice conditions do not retain the same sign in any sector for periods longer than ~6 months. Thus the results obtained here do not support the notion that Fram Strait outflow is associated with regional ice fluctuations on the multiyear timescale.

SUMMARY

Correlations between the estimated ice flux through Fram Strait and ice conditions in various sectors of the Arctic were computed for various combinations of months. A marked shift around 1972 was noted in the region for which ice coverage correlated most highly with Fram Strait outflow. The shift is consistent with changes in the large-scale atmospheric circulation pattern which, in turn, would shift the major source region of the Transpolar Drift Stream. Changes in the circulation pattern should be reflected in changes of the regional sea ice response to fluctuations of Fram Strait outflow. While the changes in the atmospheric circulation may be consequences of forcing from within or from beyond the Arctic, the ultimate cause of the atmospheric changes was not addressed here.

The correlation between parameterized outflow of ice in the Fram Strait and subsequent summer ice conditions in the Alaskan/Siberian sectors implies that the response to wind-forcing in the Fram Strait is not localized. Rather, there is the suggestion that above-normal outflow of multiyear ice during the winter/spring months may precondition the large-scale pack to respond more directly to offshore flow events occurring over the Alaskan/Siberian sectors during subsequent months. This greater susceptibility to summertime evacuation of the coastal waters may indeed be the basis of the Soviets' use of the Fram Strait outflow in predictive applications. While the scales of the apparent response are perhaps surprising, they merit further investigations drawing upon observationally-based wind/drift comparisons as well as large-scale ice model simulations of years characterized by above- and below-normal outflow through the Fram Strait.

Finally, the results obtained here illustrate one of the most serious limitations of empirical analyses of geophysical data. Relationships between two variables may change substantially from one time period to the next. Extrapolations to independent data, and particularly applications in real-time forecasting, may therefore result in a severe loss of the apparent "signal" or skill indicated by the dependent data.

Acknowledgements. This work was supported through the Navy Center for International Science and Technology under ONR Contract N00014-87-C-0039 and by the Office of Naval Research through its support of the Chair in Arctic Marine Science. We wish to thank Norene McGhiey and Maureen Thompson for typing the manuscript, and Becky Ross for drafting the figures.

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FIGURE CAPTIONS

Fig. 1. General pattern of sea ice drift in the Arctic Ocean (from Wittmann *et al.*, 1961).

Fig. 2. Time series of annual average pressure differences across Fram Strait (80°N, 20°W - 80°N, 10°E). Scale of corresponding wind-driven outflow, based on the ratio of 1 mb:6600 km^2/mo, is shown at right.

Fig. 3. Ice concentration grid (Walsh and Johnson, 1979). Heavy solid lines show the boundary of area used to compute northern Alaskan ice coverage and the Fram Strait transect used to compute mean concentration for adjustment of ice outflow in Table 2c.

Fig. 4. Correlations between northern Alaskan ice coverage and the calculated Fram Strait ice flux for the Soviets' dependent years (1955-71, solid squares) and independent years (1972-84, solid circles). Equation numbers correspond to Table 1. All correlations are based on non-Soviet data described in text.

Fig. 5. Correlations between June-August ice coverage in 20° longitudinal sectors and pressure differences across Fram Strait during 5-month period centered on indicated month. Solid contours denote negative correlations, dashed contours positive correlations. Correlations are shown for 1953-71 (upper panel) and 1972-84 (lower panel).

Fig. 6. Mean sea level pressures for January-July of (a) 1953-71 and (b) 1972-84.

Fig. 7. Time series of Fram Strait pressure difference, May-September (solid line) and northern Alaskan ice coverage, June-October (dashed line).

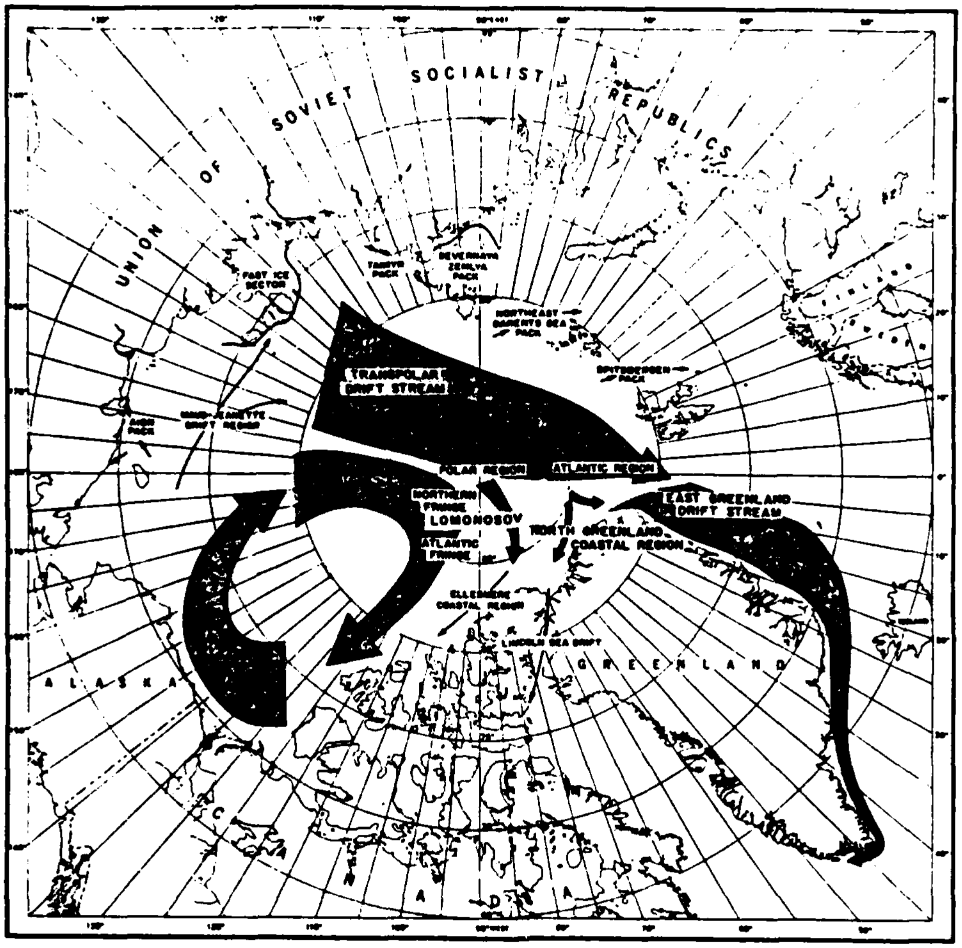
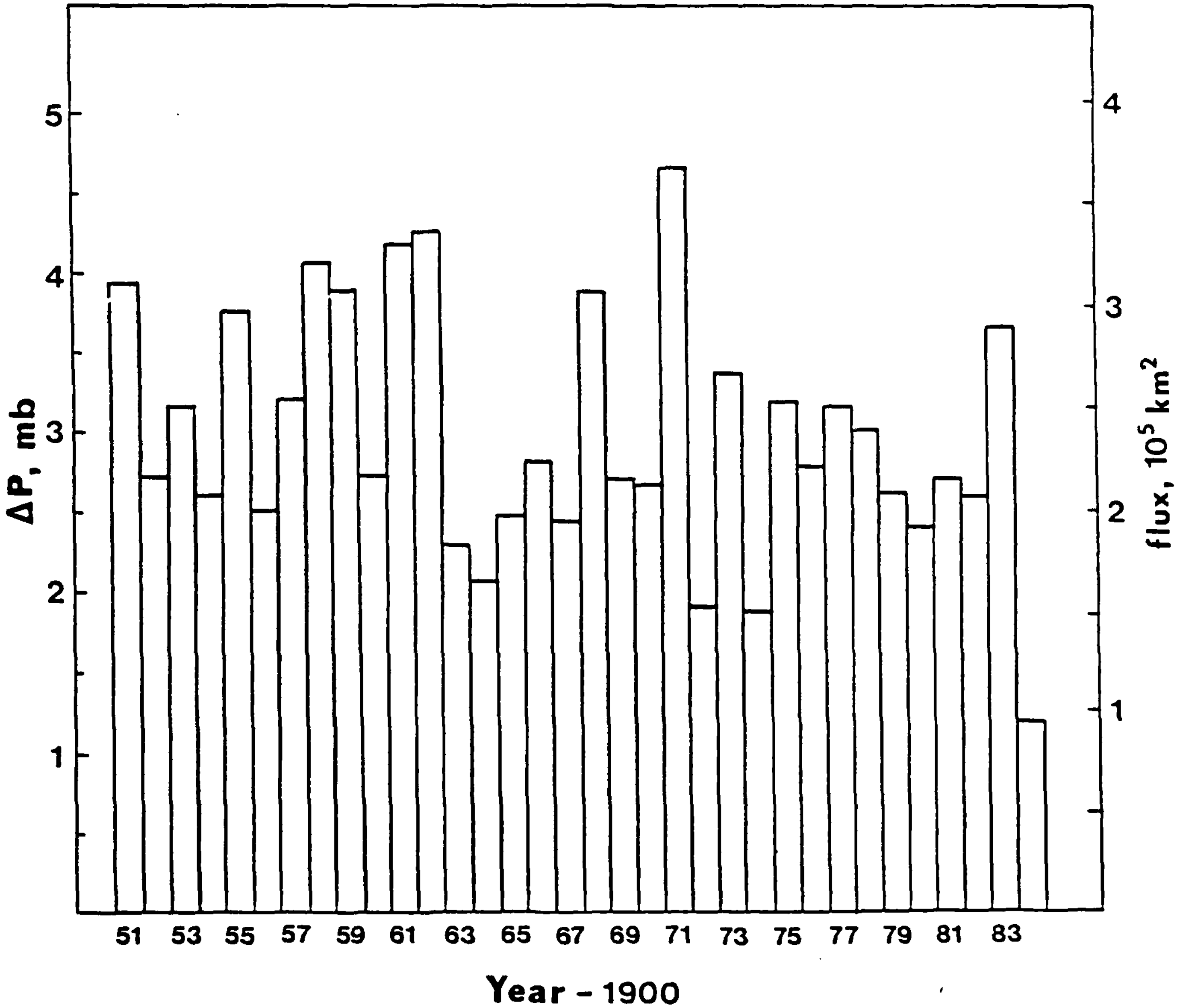


Fig. 1. General pattern of sea ice drift in the Arctic Ocean (from Wittmann et al., 1961).



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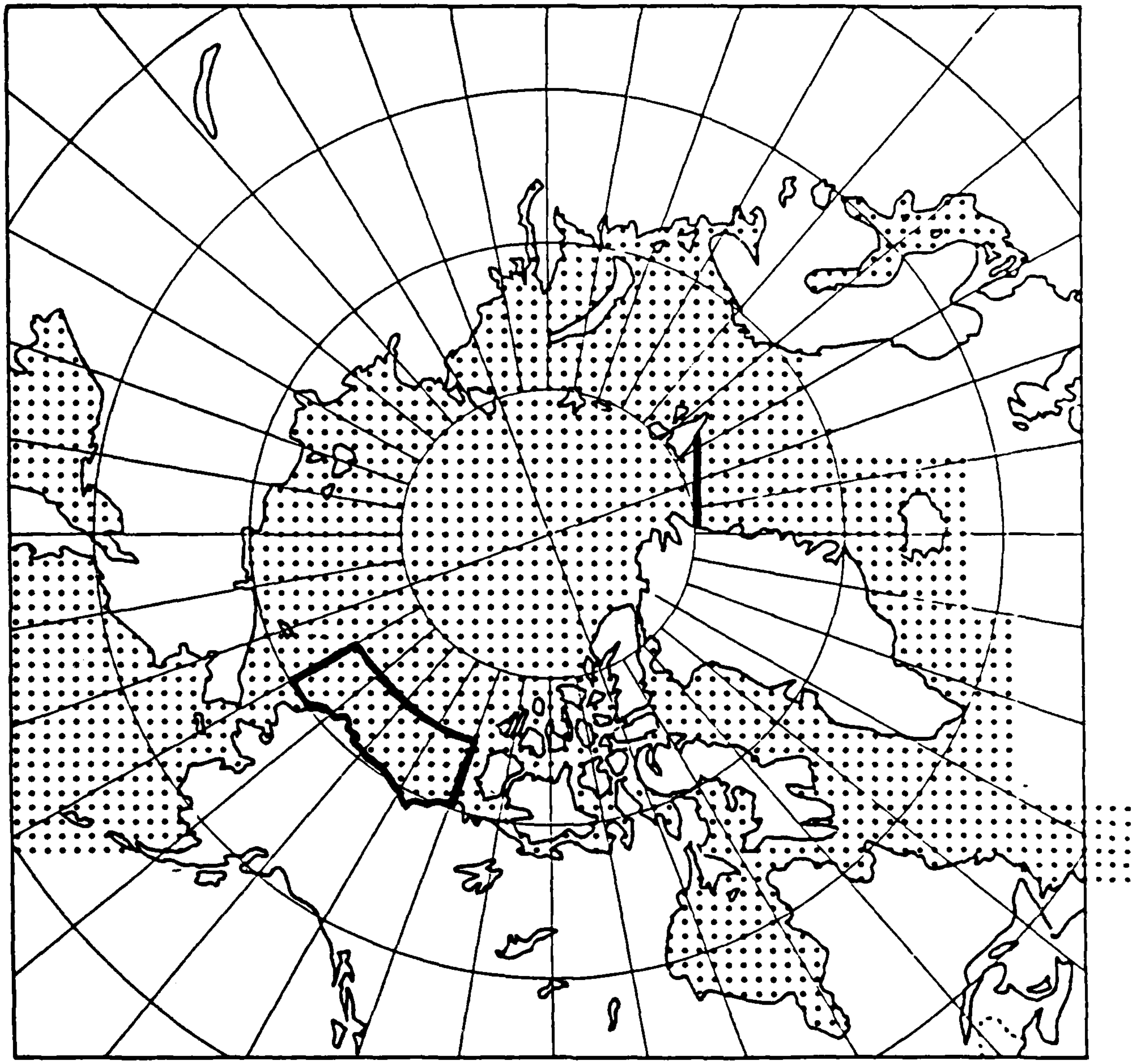

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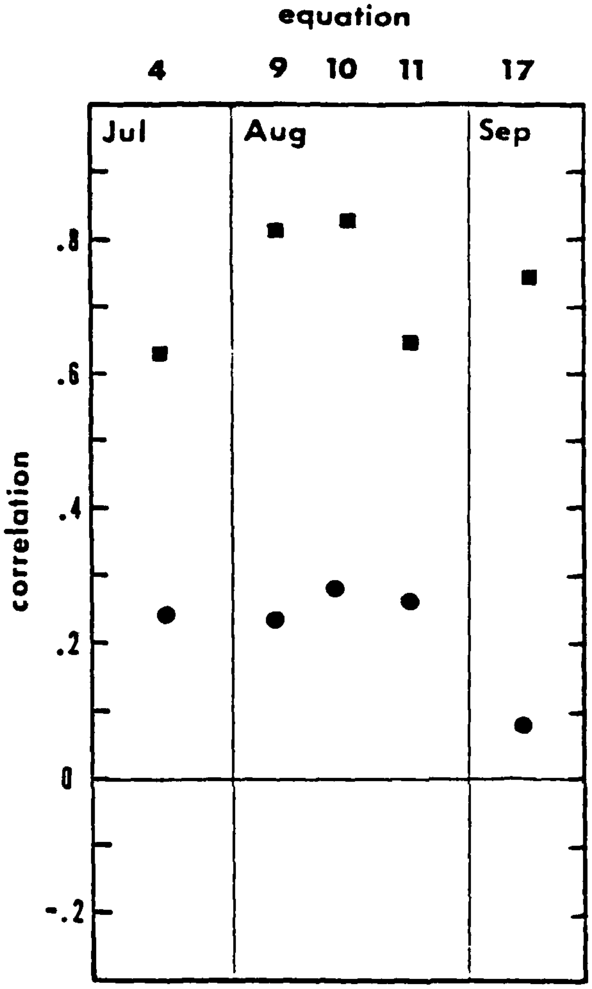
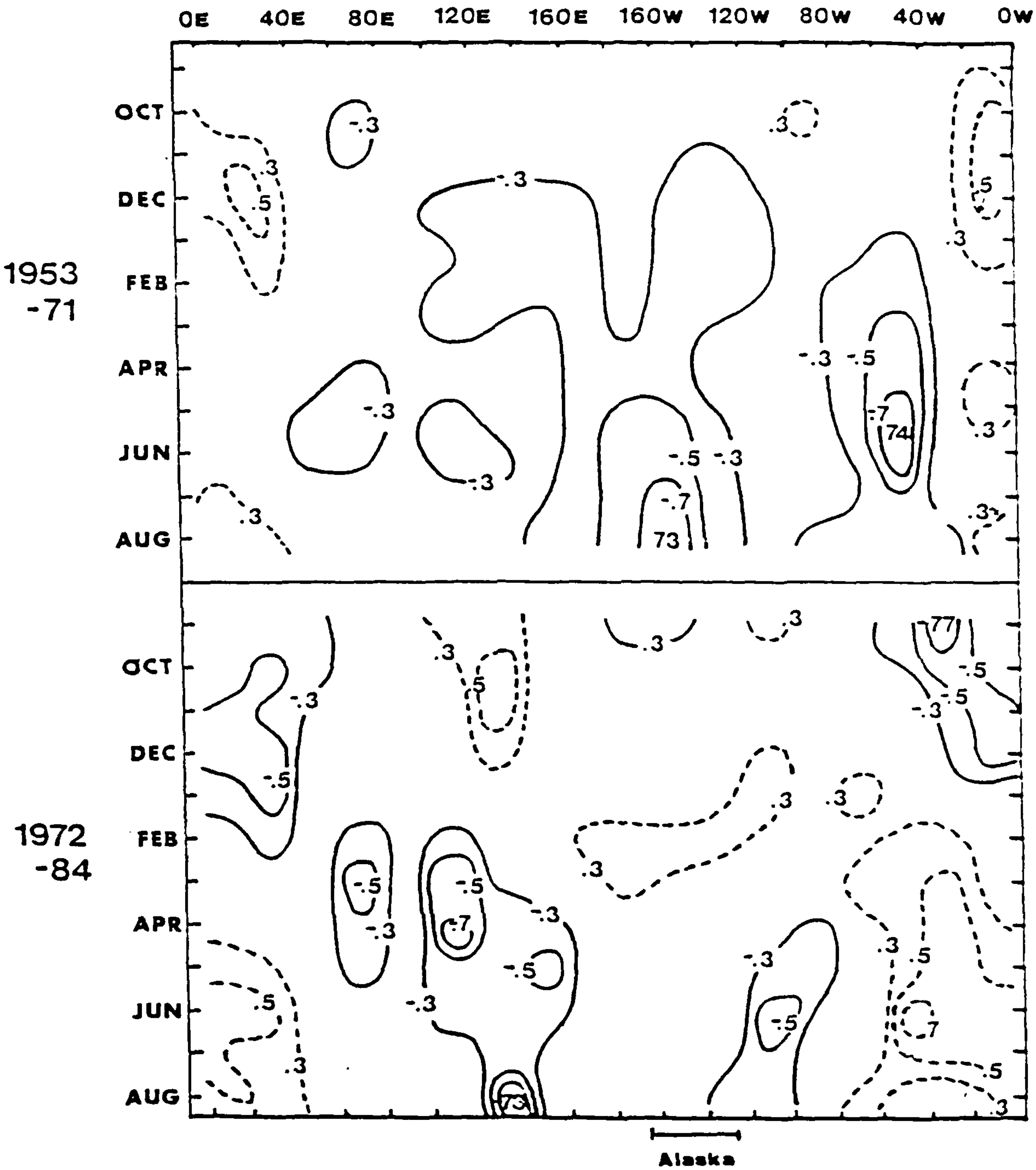


Fig. 4. Correlations between northern Alaskan ice coverage and the calculated Fram Strait ice flux for the Soviets' dependent years (1955-71, solid squares) and independent years (1972-84, solid circles). Equation numbers correspond to Table 1. All correlations are based on non-Soviet data described in text.



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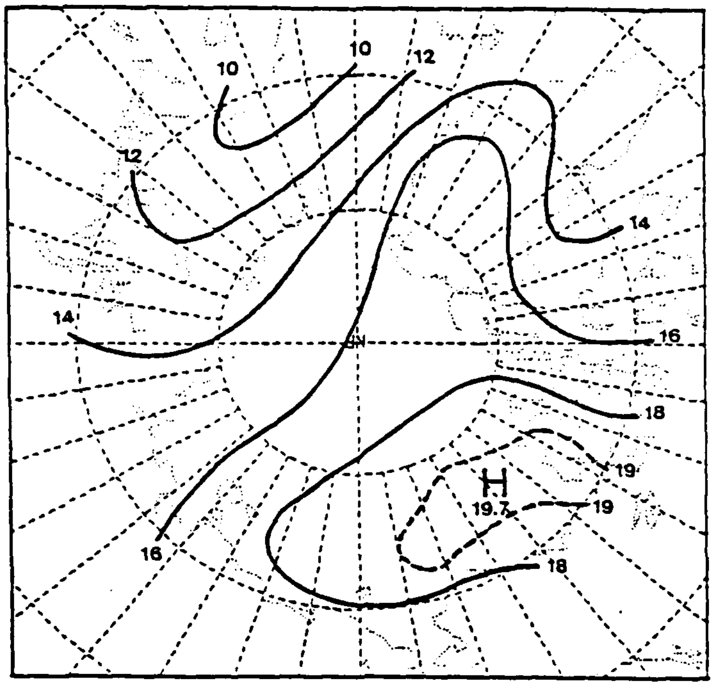
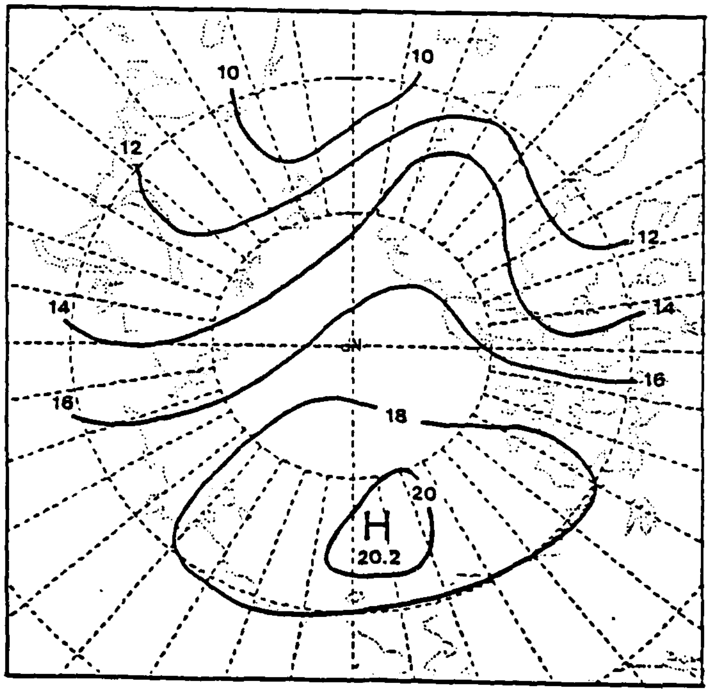


(a) 1953-1971



(b) 1972-1984

Fig. 6. Mean sea level pressures for January-July of (a) 1953-71 and (b) 1972-84.

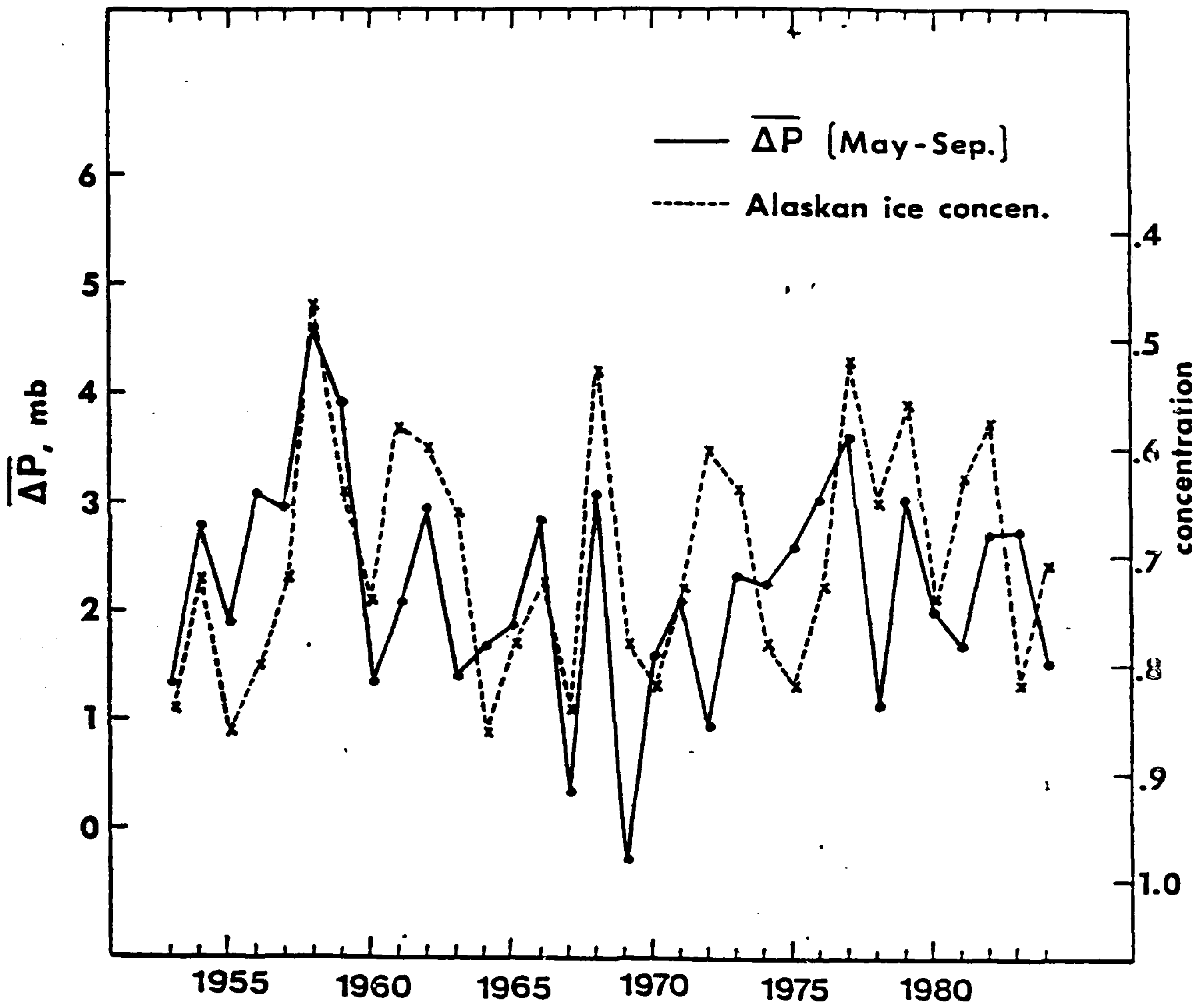


Fig. 7. Time series of Fram Strait pressure difference, May-September (solid line) and northern Alaskan ice coverage, June-October (dashed line).

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